# Physics at a
# Fermilab Proton Driver

April 5, 2005

# Executive Summary

In the last few years there has been interest in a new generation of high intensity multi-GeV proton accelerators. This interest is motivated by the exciting discoveries that have been made in the neutrino sector; namely that neutrinos have mass and that neutrinos of one flavor can transform themselves into neutrinos of a different flavor as they propagate over macroscopic distances. This is exciting because it requires new physics beyond the Standard Model. However, we do not yet have a complete knowledge of neutrino masses and mixings. Understanding these neutrino properties is important because neutrinos are the most ubiquitous matter particles in the universe. In number, they exceed the constituents of ordinary matter (electrons, protons, neutrons) by a factor of ten billion. They probably account for at least as much energy in the universe as all the stars combined and, depending on their exact masses, might also account for a few percent of the so-called "dark matter". In addition, neutrinos are important in stellar processes. There are about $7 \times 10^{10}$ cm$^{-2}$ sec$^{-1}$ streaming through the Earth from the Sun. Neutrinos govern the dynamics of supernovae, and hence the production of heavy elements in the universe. Furthermore, if there is CP Violation in the neutrino sector, the physics of neutrinos in the early universe might ultimately be responsible for Baryogenesis. *If we are to understand "why we are here" and the basic nature of the universe in which we live, we must understand the basics properties of the neutrino.*

To identify the best ways to address the most important open neutrino questions, and to determine an effective, fruitful U.S. role within a global experimental neutrino program, the American Physical Society's Divisions of Nuclear Physics and Particles and Fields, together with the Divisions of Astrophysics and the Physics of Beams, have recently conducted a "Study on the Physics of Neutrinos". This study recommended *"... as a high priority, a comprehensive U.S. program to complete our understanding of neutrino mixing, to determine the character of the neutrino mass spectrum, and to search for CP violation among neutrinos."* , and identified, as a key ingredient of the future program, *"A proton driver in the megawatt class or above and neutrino superbeam with an appropriate very large detector capable of observing CP violation and measuring the neutrino mass-squared differences and mixing parameters with high precision."* The proposed Fermilab Proton Driver would, together with a suitable new detector, fulfill this need by providing a 2 megawatt proton beam at Main Injector (MI) energies for the future NuMI program.

The NuMI beam is unique. It is the only neutrino beam that has an appropriate energy and a sufficiently long baseline to produce, due to matter effects, significant changes in the effective oscillation parameters. These matter effects can be exploited to determine the pattern of neutrino masses. Furthermore, when combined with measurements from the much shorter-baseline T2K experiment being built in Japan, an appropriate NuMI-based experiment could exploit matter effects to achieve a greatly enhanced sensitivity to CP violation in the neutrino sector.

To obtain sufficient statistical sensitivity to determine the pattern of neutrino masses and search for CP violation over a significant region of parameter-space will require a new detector with a fiducial mass of a few times 10 kt, and a neutrino beam with the highest practical intensity. Hence, the primary motivation for the new Fermilab Proton Driver is to enable an increase in the MI beampower to the maximum that is considered practical, namely 2 megawatts. The achievable sensitivity to the pattern of neutrino masses, and to CP violation, will depend on the unknown neutrino mixing angle $\theta_{13}$. Experiments using the NuMI beam in the Fermilab Proton Driver era would be able to search for a finite $\theta_{13}$ with a sensitivity well beyond that achievable with the present NuMI beam, the T2K beam, or at future reactor experiments.

Two possible schemes have been proposed for implementing a 2 megawatt proton driver at Fermilab. The presently favored scheme is based on a new 8 GeV superconducting (SC) linac that utilizes, and helps develop, Linear Collider technology. The MI fill time is very short (<1 ms), which means that the MI can deliver 2 megawatts of beam at any energy from 40 to 120 GeV, and improvements to the MI ramp time can further increase the beam power. The short fill time also means that the majority of the 8 GeV cycles will not be used by the MI. Hence the SC linac could support a second high-intensity physics program using the primary beam at 8 GeV with an initial beam power of 0.5 megawatts, upgradeable to 2 megawatts. Both the primary proton beams (MI and 8 GeV) could be used to create neutrino beams. Both these beams are needed for an extensive program of neutrino scattering measurements. These measurements are not only of interest in their own right, but are also needed to reduce the systematic uncertainties on the neutrino oscillation measurements which arise from our limited knowledge of the relevant neutrino cross sections.

Although neutrino oscillations provide the primary motivation for interest in the Fermilab Proton Driver, the community participating in recent proton driver physics workshops has been broader than the neutrino physics community. Note that intense muon, pion, kaon, neutron, and antiproton beams at the Fermilab Proton Driver would offer great flexibility for the future program, and could support a diverse program of experiments of interest to particle physicists, nuclear physicists, and nuclear-astrophysicists. In particular it has been realized that, as the LHC begins to probe the energy frontier, a new round of precision flavor physics experiments would provide information that is complementary to the LHC data by indirectly probing high mass scales through radiative corrections. This would help to elucidate the nature of any new physics that is discovered at the energy frontier. Should no new physics be discovered at the LHC then, for the foreseeable future, precision muon, pion, kaon, and neutron measurements at a high-intensity proton source may provide the only practical way to probe physics at mass scales beyond the reach of the LHC.

The main conclusions presented in this report are:

- Independent of the value of the unknown mixing angle $\theta_{13}$ an initial Fermilab Proton Driver long-baseline neutrino experiment would be expected to make a critical contribution to the global oscillation program.

- If $\theta_{13}$ is very small the initial Fermilab Proton Driver experiment would be expected to provide the most stringent limit on $\theta_{13}$ and prepare the way for a neutrino factory. The expected $\theta_{13}$ sensitivity exceeds that expected for reactor-based experiments, or any other accelerator-based experiments.

- If $\theta_{13}$ is sufficiently large the initial Fermilab Proton Driver experiment would be expected to precisely measure its value, perhaps determine the mass hierarchy, and prepare the way for a sensitive search for CP violation. The value of $\theta_{13}$ will guide the further evolution of the Proton Driver neutrino program.

- The Fermilab Proton Driver neutrino experiments would also make precision measurements of the other oscillation parameters, and conduct an extensive set of neutrino scattering measurements, some of which are important for the oscillation program. Note that the neutrino scattering measurements require the highest achievable intensities at both MI energies and at 8 GeV.

- The Fermilab Proton Driver could also support a broad range of other experiments of interest to particle physicists, nuclear physicists, and nuclear astrophysicists. These experiments could exploit antiproton- and kaon-beams from the MI, or muon-, pion-, or neutron-beams from the 8 GeV linac. These "low energy" experiments would provide sensitivity to new physics at high mass scales which would be complementary to measurements at the LHC and beyond.

# Contents

# 1 Introduction

In the last few years there has been interest in a new generation of high intensity multi-GeV proton accelerators capable of delivering a beam of one or a few megawatts. The interest in these high-intensity accelerators is driven by the exciting discoveries that have been made in the neutrino sector; namely that neutrinos have mass and that neutrinos of one flavor can transform themselves into neutrinos of a different flavor as they propagate over macroscopic distances. This requires new physics beyond the Standard Model. To identify the most important open neutrino physics questions, evaluate the physics reach of various proposed ways of answering the questions, and to determine an effective, fruitful U.S. role within a global experimental neutrino program, the American Physical Society's Divisions of Nuclear Physics and Particles and Fields, together with the Divisions of Astrophysics and the Physics of Beams, have recently conducted a "Study on the Physics of Neutrinos". The resulting APS report [1] recommended *"... as a high priority, a comprehensive U.S. program to complete our understanding of neutrino mixing, to determine the character of the neutrino mass spectrum, and to search for CP violation among neutrinos."* The APS study identified, as a key ingredient of the future program, *"A proton driver in the megawatt class or above and neutrino superbeam with an appropriate very large detector capable of observing CP violation and measuring the neutrino mass-squared differences and mixing parameters with high precision."* A Fermilab Proton Driver would, together with a suitable new detector, fulfill this need by providing a 2 megawatt proton beam at Main Injector (MI) energies for the future NuMI program.

Fermilab hosts the U.S. accelerator-based neutrino program and, with the recently completed NuMI beamline, is operating the longest-baseline neutrino beam in the World. The NuMI beam will, for the foreseeable future, provide the only accelerator-based neutrino baseline that is long enough for matter effects to significantly change the effective neutrino oscillation parameters. These matter effects can be exploited to answer one of the key questions in neutrino physics, namely: Which of the two presently viable patterns of neutrino mass is the correct one ? Furthermore, when combined with measurements from the much shorter-baseline T2K experiment being built in Japan, an appropriate NuMI-based experiment could exploit matter effects and achieve a greatly enhanced sensitivity to CP violation in the neutrino sector.

To obtain sufficient statistical sensitivity to determine the pattern of neutrino masses and search for CP violation over a significant region of parameter -space will require a new detector with a fiducial mass of a few times 10 kt, and a neutrino beam with the highest practical intensity. Hence, the primary motivation for the new Fermilab Proton Driver is to enable an increase in the MI beam power to the maximum that is considered practical, namely 2 megawatts. The achievable sensitivity to the pattern of neutrino masses, and to CP violation, will depend on the unknown neutrino mixing angle $\theta_{13}$. Experiments using the NuMI beam in the Fermilab Proton Driver era would be able to search for a finite $\theta_{13}$ with a sensitivity well beyond that achievable with the present NuMI beam, the T2K beam, or at future reactor experiments. For this reason the APS neutrino study report recommended a new proton driver be constructed as early as is practical. In the illustrative road map given in the

APS report, construction begins in 2008, with operation beginning in 2012. In the longer term, should $\theta_{13}$ turn out to be close to or beyond the limiting sensitivity of the first round of Fermilab Proton Driver experiments, the Fermilab Proton Driver would offer options for further upgrades to the detector and/or beamline to yield another incremental improvement in sensitivity. There would also be an option to develop the Fermilab Proton Driver complex to support a neutrino factory which would enable a two orders of magnitude improvement in sensitivity.

Two possible schemes have been proposed for implementing a 2 megawatt proton driver at Fermilab. In Scheme 1 the existing Fermilab Booster is replaced with a new 8 GeV synchrotron operating at 15 Hz. It takes five booster cycles (1/3 of a second) to fill the MI. This limits the maximum repetition rate, and hence limits the ultimate beam power that can be delivered. Scheme 2 is based on a new 8 GeV superconducting (SC) linac that utilizes, and helps develop, Linear Collider technology. The MI fill time is very short ($< 1$ ms), which means that the MI can deliver 2 megawatts of beam at any energy from 40 to 120 GeV, and that improvements to the MI ramp time can further increase the beam power. The short fill time also means that the majority of the 8 GeV cycles will not be used by the MI. Hence the SC linac could support a second high-intensity physics program using the primary beam at 8 GeV with an initial beam power of 0.5 megawatts, upgradeable to 2 megawatts.

Although neutrino oscillations provide the primary motivation for interest in the Fermilab Proton Driver, the community participating in recent proton driver physics workshops has been broader than the neutrino physics community. Note that intense muon, pion, kaon, neutron, and antiproton beams at the Fermilab Proton Driver would offer great flexibility for the future program, and could support a diverse program of experiments of interest to particle physicists, nuclear physicists, and nuclear-astrophysicists. In particular it has been realized that, as the LHC begins to probe the energy frontier, a new round of precision flavor physics experiments would provide information that is complementary to the LHC data by indirectly probing high mass scales through radiative corrections. This would help to elucidate the nature of any new physics that is discovered at the energy frontier. Should no new physics be discovered at the LHC then, for the foreseeable future, precision muon, pion, kaon, and neutron measurements at a high-intensity proton source may provide the only practical way to probe physics at mass scales beyond the reach of the LHC.

This document summarizes the physics opportunities that would be provided by a new proton driver at Fermilab. In particular, the physics that could be done with a 2 megawatt MI beam, and the physics that could be done with a 0.5 - 2 megawatt 8 GeV beam. Sections 2 and 3 describe respectively the potential neutrino oscillation and neutrino scattering physics programs. Section 4 describes the broader physics program using muon-, pion-, and neutron-beams produced with a high intensity primary proton beam at 8 GeV (relevant for the SC linac option), and using kaon- and antiproton-beams produced with the MI primary proton beam (relevant to both SC linac and synchrotron schemes). An overview of the complete proton driver program is given in Section 5, and a summary in Section 6.

# 2 Neutrino Oscillations

Neutrinos are the most ubiquitous matter particles in the universe. In number, they exceed the constituents of ordinary matter (electrons, protons, neutrons) by a factor of ten billion. They probably account for at least as much energy in the universe as all the stars combined and, depending on their exact masses, might also account for a few percent of the so-called "dark matter". In addition, neutrinos are important in stellar processes. There are about $7 \times 10^{10}$ cm$^{-2}$ sec$^{-1}$ streaming through the Earth from the Sun. Neutrinos govern the dynamics of supernovae, and hence the production of heavy elements in the universe. Furthermore, if there is CP Violation in the neutrino sector, the physics of neutrinos in the early universe might ultimately be responsible for Baryogenesis. *If we are to understand "why we are here" and the basic nature of the universe in which we live, we must understand the basic properties of the neutrino.*

In the last few years solar, atmospheric, and reactor neutrino experiments have revolutionized our understanding of the nature of neutrinos. We now know that neutrinos produced in a given flavor eigenstate can transform themselves into neutrinos of a different flavor as they propagate over macroscopic distances. This means that, like quarks, neutrinos have a non-zero mass, the flavor eigenstates are different from the mass eigenstates, and hence neutrinos mix. However, we have incomplete knowledge of the properties of neutrinos since *we do not know the spectrum of neutrino masses, and we have only partial knowledge of the matrix that describes the mixing between the three known neutrino flavor eigenstates.* Furthermore, it is possible that the simplest three-flavor mixing scheme is not the whole story, and that a complete understanding of neutrino properties will require a more complicated framework. In addition to determining the parameters that describe the neutrino sector, the three-flavor mixing framework must also be tested.

The Standard Model cannot accommodate non-zero neutrino mass terms without some modification. We must either introduce right-handed neutrinos (to generate Dirac mass terms) or allow neutrinos to be their own antiparticle (violating lepton number conservation, and allowing Majorana mass terms). Hence *the physics of neutrino masses is physics beyond the Standard Model.* Although we do not know the neutrino mass spectrum, we do know that the masses, and the associated mass-splittings, are tiny compared to the masses of any other fundamental fermion. This suggests that the physics responsible for neutrino mass will include new components radically different from those of the Standard Model. Furthermore, although we do not have complete knowledge of the neutrino mixing matrix, we do know that it is qualitatively very different from the corresponding quark mixing matrix. The observed difference necessarily constrains our ideas about the underlying relationship between quarks and leptons, and hence models of quark and lepton unification in general, and Grand Unified Theories (GUTs) in particular. Note that in neutrino mass models the seesaw mechanism provides a quantitative explanation for the observed small neutrino masses, which arise as a consequence of the existence of right-handed neutral leptons at the GUT-scale. Over the last few years, as our knowledge of the neutrino oscillation parameters has improved, a previous generation of neutrino mass models has already been ruled out, and a new set of models has emerged specifically designed to accommodate the neutrino parameters. Further improvement in our knowledge of the oscillation parameters will necessarily reject many of these models, and presumably encourage the emergence of new ideas. Hence *neutrino physics is experimentally driven, and the experiments are already directing our ideas about what lies beyond the Standard Model.*

Our desire to understand both the universe in which we live and physics beyond the Standard Model provides a compelling case for an experimental program that can elucidate the neutrino mass spectrum and mixing matrix, and test the three-flavor mixing framework. It seems likely that complete knowledge of the neutrino mass splittings and of the mixing matrix is accessible to accelerator-based neutrino oscillation experiments. In the following we first introduce the three-flavor mixing framework and identify the critical measurements that need to be made in the future oscillation physics program. The sensitivity of the Fermilab program based on a new 2 Megawatt Proton Driver is then considered in the context of the global experimental program.

## 2.1 Oscillation Framework and Measurements

There are three known neutrino flavor eigenstates $\nu_\alpha = (\nu_e,\ \nu_\mu,\ \nu_\tau)$. Since transitions have been observed between the flavor eigenstates we now know that neutrinos have finite masses, and that there is mixing between the flavor eigenstates. The mass eigenstates $\nu_i = (\nu_1,\ \nu_2,\ \nu_3)$ with masses $m_i = (m_1,\ m_2,\ m_3)$ are related to the flavor eigenstates by a $3 \times 3$ mixing matrix $U^\nu$,

$$|\nu_\alpha\rangle = \sum_i U^\nu_{\alpha i} |\nu_i\rangle \tag{1}$$

The matrix $U^\nu$ is unitary and hermitian. Only four numbers are needed to specify all of the matrix elements, namely three mixing angles $(\theta_{12}, \theta_{23}, \theta_{13})$ and one complex phase $(\delta)$. In terms of these parameters

$$U^\nu = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix} \tag{2}$$

where $c_{jk} \equiv \cos\theta_{jk}$ and $s_{jk} \equiv \sin\theta_{jk}$. Neutrino oscillation measurements have already provided some knowledge of $U^\nu$, which is approximately given by:

$$U^\nu = \begin{pmatrix} 0.8 & 0.5 & ? \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \tag{3}$$

We have no knowledge of the (1,3)-element of the mixing matrix. This matrix element is parametrized by $s_{13}e^{-i\delta}$. We have only an upper limit on $\theta_{13}$ and no knowledge of $\delta$. Note that $\theta_{13}$ and $\delta$ are particularly important because if $\theta_{13}$ and $\sin\delta$ are non-zero there will be CP violation in the neutrino sector.

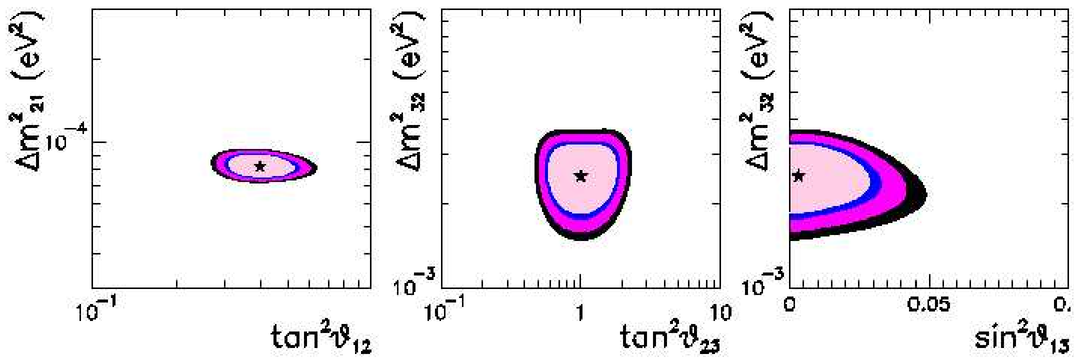


Figure 1: Current experimental constraints on the three mixing angles $\theta_{12}$, $\theta_{23}$, and $\theta_{13}$ and their dependence on the two known mass-squared differences $\Delta m^2_{12}$ and $\Delta m^2_{23}$. The star indicates the most likely solution. The contours correspond to certain confidence levels. Figure taken from [1].

Neutrino oscillations are driven by the splittings between the neutrino mass eigenstates. It is useful to define the differences between the squares of the masses of the mass eigenstates $\Delta m^2_{ij} \equiv m^2_i - m^2_j$. The probability that a neutrino of energy $E$ and initial flavor $\alpha$ will "oscillate" into a neutrino of flavor $\beta$ is given by $P_{\alpha\beta} \equiv P(\nu_\alpha \to \nu_\beta) = |\langle\nu_\beta|\exp(-i\mathcal{H}t)|\nu_\alpha\rangle|^2$, which in vacuum is given by

$$P_{\alpha\beta} = \left|\sum_{j=1}^{3} U^*_{\alpha j} U_{\beta j} \exp(-iE_j t)\right|^2 = \sum_{j=1}^{3}\sum_{k=1}^{3} U_{\alpha j} U^*_{\alpha k} U^*_{\beta j} U_{\beta k} \exp\left(-i\frac{\Delta m^2_{kj}}{2E}t\right) \tag{4}$$

If neutrinos of energy $E$ travel a distance $L$ then a measure of the propagation time $t$ is given by $L/E$. Non-zero $\Delta m^2_{ij}$ will result in neutrino flavor oscillations that have maxima at given values of $L/E$, and oscillation amplitudes that are determined by the matrix elements $U^\nu_{\alpha i}$, and hence by $\theta_{12}, \theta_{23}, \theta_{13}$, and $\delta$.

Our present knowledge of the neutrino mass splittings and mixing matrix, which has been obtained from atmospheric-, solar-, reactor-based-, and accelerator-based-neutrino experiments, is summarized in Fig. 1. The solar-neutrino experiments and the reactor experiment KamLAND probe values of $L/E$ that are sensitive to $\Delta m^2_{21}$, and the mixing angle $\theta_{12}$. Our knowledge of these parameters is shown in the left panel of Fig. 1. The atmospheric-neutrino experiments and the accelerator based experiment K2K probe values of $L/E$ that are sensitive to $\Delta m^2_{32}$, and the mixing angle $\theta_{23}$. Our knowledge of these parameters is shown in the central panel of Fig. 1. Searches for $\nu_\mu \leftrightarrow \nu_e$ transitions with values of $L/E$ corresponding to the atmospheric-neutrino scale are sensitive to the third mixing angle $\theta_{13}$. To date these searches have not observed this transition, and hence we have only an upper limit on $\theta_{13}$, which is shown in the right panel of Fig. 1.

The mixing angles tell us about the flavor content of the neutrino mass eigenstates. Our knowledge of the $\Delta m^2_{ij}$ and the flavor content of the mass eigenstates is summarized in Fig. 2. Note that there are two possible patterns of neutrino mass. This is because the neutrino oscillation experiments to date have been sensitive to

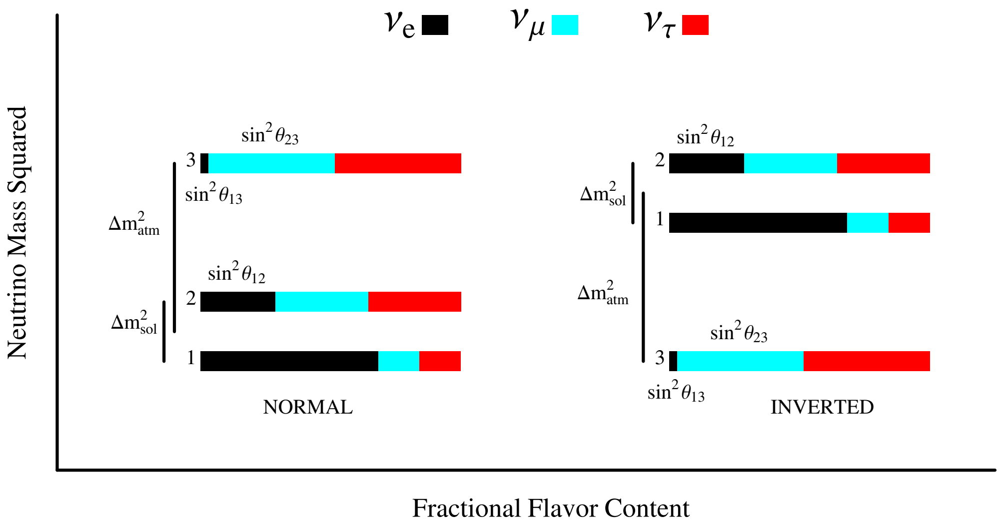


Figure 2: The two possible arrangements of the masses of the three known neutrinos, based on neutrino oscillation measurements. The spectrum on the left corresponds to the *Normal Hierarchy* and has $\Delta m^2_{32} > 0$. The spectrum on the right corresponds to the *Inverted Hierarchy* and has $\Delta m^2_{32} < 0$. The $\nu_e$ fraction of each mass eigenstate is indicated by the black solid region. The $\nu_\mu$ and $\nu_\tau$ fractions are indicated by the blue (red) regions respectively. The $\nu_e$ fraction in the mass eigenstate labeled "3" has been set to the CHOOZ bound.

the magnitude of $\Delta m^2_{32}$, but not its sign. The neutrino spectrum shown on the left in Fig. 2 is called the *Normal Mass Hierarchy* and corresponds to $\Delta m^2_{32} > 0$. The neutrino spectrum shown on the right is called the *Inverted Mass Hierarchy* and corresponds to $\Delta m^2_{32} < 0$. The reason we don't know the sign of $\Delta m^2_{32}$, and hence the neutrino mass hierarchy, is that neutrino oscillations in vacuum depend only on $|\Delta m^2_{32}|$. However, in matter the effective parameters describing neutrino transitions involving electron-type neutrinos are modified in a way that is sensitive to the sign of $\Delta m^2_{32}$. An experiment with a sufficiently long baseline in matter and an appropriate $L/E$ can therefore determine the neutrino mass hierarchy.

Finally, it should be noted that there is a possible complication to the simple three-flavor neutrino oscillation picture. The LSND [2] experiment has reported evidence for muon anti-neutrino to electron anti-neutrino transitions for values of $L/E$ which are less than two orders of magnitude smaller than the corresponding values observed for atmospheric neutrinos. The associated transition probability is very small, of the order of 0.3%. If this result is confirmed by the MiniBooNE [3] experiment, it will require a third characteristic $L/E$ range for neutrino flavor transitions. Since each $L/E$ range implies a different mass-splitting between the participating neutrino mass eigenstates, confirmation of the LSND result would require more than three mass eigenstates. This would be an exciting and radical development. Independent of whether the LSND result is confirmed or not, it is important that the future global neutrino oscillation program is able to make further tests of the three-flavor oscillation framework.

In summary, to complete our knowledge of the neutrino mixing matrix and the pattern of neutrino masses we must measure $\theta_{13}$ and $\delta$, determine the sign of $\Delta m^2_{32}$, and test the three-flavor mixing framework. The primary, initial goal for a Fermilab Proton Driver will be to make these measurements.

## 2.2 The Importance of the Unanswered Questions

Non-zero neutrino masses require physics beyond the Standard Model (SM). The determination of neutrino masses and mixings will discriminate between various neutrino models (see, for example, Ref. [4–8]) and yield clues that will help determine whether physics beyond the SM is described by a Grand Unified Theory or some other theoretical framework.

The basic neutrino questions that we would like to address with a Fermilab Proton Driver are:

**What is the order of magnitude of $\theta_{13}$?**

**Is the mass hierarchy normal or inverted?**

**Is there CP Violation in the neutrino sector and what is the value of $\delta$?**

These questions are discussed in the following sections

### 2.2.1 The importance of $\theta_{13}$

Neutrino oscillation experiments have shown that two of the neutrino mixing angles ($\theta_{23}$ and $\theta_{12}$) are large. This was a surprise since the equivalent mixing angles in the quark mixing matrix are small. We have only an upper limit on the third neutrino mixing angle $\theta_{13}$. From this limit we know that $\theta_{13}$ is much smaller than $\theta_{23}$ or $\theta_{12}$. However we have no good reason to expect it to be very small. Predictions from recent models are listed in Table 1. Most of the presently viable neutrino mass models predict that $\theta_{13}$ is close to the present bound. A value of $\theta_{13}$ much smaller than the bound would suggest a new flavor symmetry that suppresses mixing in the (13)-sector. However, even if $\theta_{13}$ is exactly zero at the GUT scale, radiative corrections would be expected to drive its value away from zero at laboratory energies. If $\theta_{13}$ is determined to be much smaller than the present bound we may suspect a new lepton flavor symmetry. If $\theta_{13}$ is extremely small, such that $\sin^2 2\theta_{13} << 0.001$ for example, its value may place the GUT concept under pressure. In any case *determining the order of magnitude of $\theta_{13}$ will discriminate between theoretical models (Table 1) and provide crucial guidance toward an understanding of the physics of neutrino masses.*

In addition to its theoretical importance, the order of magnitude of $\theta_{13}$ has important experimental consequences. If $\theta_{13}$ is within an order of magnitude of its present bound we will know its value before the "Proton Driver Era". A Fermilab Proton Driver would then enable the mass hierarchy to be determined and a search for CP violation to be made. If $\theta_{13}$ is small ($\sin^2 2\theta_{13} < 0.01$) we will not know its value before the Proton Driver Era. The initial Fermilab Proton Driver program would then

| Model(s) | Refs. | $\sin\theta_{13}$ | $\sin^2 2\theta_{13}$ |
|---|---|---|---|
| Minimal SO(10) | [9] | 0.18 | 0.13 |
| Orbifold SO(10) | [10] | 0.1 | 0.04 |
| SO(10) + Flavor symmetry | [11] | $5.5\cdot 10^{-4}$ | $1.2\cdot 10^{-6}$ |
| | [12] | 0.014 | $7.8\cdot 10^{-4}$ |
| | [13–15] | 0.05 .. 0.1 | 0.01 .. 0.04 |
| | [16–18] | 0.15 .. 0.22 | 0.09 .. 0.18 |
| SO(10) + Texture | [19] | 0.01 .. 0.06 | $4\cdot 10^{-4}$ .. 0.01 |
| | [20] | 0.1 | 0.04 |
| $SU(2)_L \times SU(2)_R \times SU(4)_c$ | [21] | 0.15 | 0.09 |
| Flavor symmetries | [22–24] | 0 | 0 |
| | [25–27] | $\lesssim 0.03$ | $\lesssim 0.004$ |
| | [28–30] | 0.005 .. 0.07 | $10^{-4}$ .. 0.02 |
| | [27, 31–34] | 0.1 .. 0.2 | 0.04 .. 0.15 |
| Textures | [35] | 0.01 .. 0.05 | $4\cdot 10^{-4}$ .. 0.01 |
| | [36–39] | 0.08 .. 0.2 | 0.03 .. 0.15 |
| $3\times 2$ see-saw | [40] | 0.1 | 0.04 |
| | [41] (n.h.) | 0.07 | 0.02 |
| | (i.h.) | $> 0.006$ | $> 1.6\cdot 10^{-4}$ |
| Anarchy | [42] | $> 0.1$ | $> 0.04$ |
| Renormalization group enhancement | [43] | 0.08 .. 0.1 | 0.03 .. 0.04 |
| M-Theory model | [7] | 0.005 | $10^{-4}$ |

Table 1: Selection of predictions for $\theta_{13}$. The numbers should be considered as order of magnitude statements. The abbreviations “n.h.” and “i.h.” refer to the normal and inverted hierarchies, respectively.

improve our knowledge of $\theta_{13}$ and prepare the way for a second generation program. If $\sin^2 2\theta_{13} >\sim 0.005$ the initial Fermilab Proton Driver experiment would establish its value and might also determine the mass hierarchy, but would not be sufficiently sensitive to search for CP violation. A second generation program will be required. The options for this second generation include an upgraded detector with or without a new beamline, and a neutrino factory driven by the Proton Driver. Note that *the value of $\theta_{13}$ will determine which facilities and experiments will be needed beyond the initial Fermilab Proton Driver experiments to complete the neutrino oscillation program.*

### 2.2.2 The importance of the Mass Hierarchy

Specific neutrino mass models are usually only compatible with one of the two possible neutrino mass hierarchies (normal or inverted). A measurement of the sign of $\Delta m^2_{31}$ would therefore discriminate between models. For example, GUT models with a standard type I see-saw mechanism tend to predict a normal hierarchy (see, for example, the reviews Refs [44, 45]), while an inverted hierarchy is often obtained in models that employ flavor symmetries such as $L_e - L_\mu - L_\tau$ [46, 47].

A determination of the sign of $\Delta m^2_{31}$ would also have some consequences for neutrinoless double beta decay experiments. A negative $\Delta m^2_{31}$ would imply a lower limit on the effective mass for neutrinoless double beta decay (in the case of Majorana neutrinos) which would be expected to be within reach of the next generation of experiments.

### 2.2.3 The importance of CP Violation and $\delta$

Leptogenesis [48], in which CP Violation in the leptonic Yukawa couplings ultimately results in a baryon asymmetry in the early Universe, provides an attractive possible explanation for the observed baryon asymmetry. In the most general case, the CP phases involved in leptogenesis are not related to the low-energy CP phases that appear in the effective neutrino mass matrix [49, 50]. However, specific neutrino mass models can yield relationships between the CP violation relevant to leptogenesis and the low-energy CP phases. Examples are models in which flavor symmetries and texture zeros restrict the structure of the coupling matrices. In these models, to successfully obtain leptogenesis typically requires a non-zero phase $\delta$ (see, for example, Refs [40, 51]). Hence, although a measurement of CP Violation in the neutrino sector would not establish leptogenesis as the right explanation for the observed baryon asymmetry, it would be suggestive and a measurement of $\delta$ would discriminate between explicit neutrino mass models.

### 2.2.4 Other Oscillation Physics

With a Proton Driver the Fermilab neutrino program would provide a path to the ultimate sensitivity for measurements of $\theta_{13}$, the mass hierarchy, and CP violation. In addition to these crucial measurements, to discriminate between different theoretical models, it will also be important to improve the precision of the other oscillation parameters $(\theta_{12}, \theta_{23}, \Delta m^2_{21}, \Delta m^2_{32})$. Note that $\theta_{23}$ is of particular interest as its current, poorly determined, value is consistent with maximal mixing in the (2,3) sector. Is this mixing really maximal? Furthermore the level of consistency between the precisely measured values of the parameters in the various appearance and disappearance modes will test the 3 flavor mixing framework, possibly leading to further exciting discoveries. The Fermilab Proton Driver would not only address the value of $\theta_{13}$, the mass hierarchy, and CP violation, but would also provide a more comprehensive set of measurements that could lead to further unexpected surprises.

## 2.3 Evolution of the Sensitivity to $\theta_{13}$

In the coming years we can expect improvements in our knowledge of the oscillation parameters from the present generation of running experiments (MiniBooNE, KamLAND, K2K, MINOS, SNO, SuperK) and experiments under construction (T2K). Beyond this a new generation of reactor and accelerator based experiments are being proposed (for example the Double-CHOOZ reactor experiment and the NO$\nu$A experiment using the NuMI beam). In the coming decade the search for a non-zero $\theta_{13}$ is

| Label | $L$ | $\langle E_\nu \rangle$ | $P_{\rm Source}$ | Detector technology | $m_{\rm Det}$ | $t_{\rm run}$ |
|---|---|---|---|---|---|---|
| **Conventional beam experiments:** | | | | | | |
| MINOS | 735 km | 3 GeV | $3.7 \cdot 10^{20}$ pot/y | Magn. iron calorim. | 5.4 kt | 5 yr |
| ICARUS | 732 km | 17 GeV | $4.5 \cdot 10^{19}$ pot/y | Liquid Argon TPC | 2.35 kt | 5 yr |
| OPERA | 732 km | 17 GeV | $4.5 \cdot 10^{19}$ pot/y | Emul. cloud chamb. | 1.65 kt | 5 yr |
| **Off Axis:** | | | | | | |
| T2K | 295 km | 0.76 GeV | $1.0 \cdot 10^{21}$ pot/y | Water Cherenkov | 22.5 kt | 5 yr |
| NO$\nu$A$^\dagger$ | 812 km | 2.22 GeV | $4.0 \cdot 10^{20}$ pot/y | Low-Z-calorimeter | 50 kt | 5 yr |
| **Reactor experiments:** | | | | | | |
| D-Chooz$^\dagger$ | 1.05 km | $\sim 4$ MeV | $2 \times 4.25$ GW | Liquid Scintillator | 11.3 t | 3 yr |
| Reactor-II$^\dagger$ | 1.70 km | $\sim 4$ MeV | 8 GW | Liquid Scintillator | 200 t | 5 yr |

† proposed

Table 2: The different classes of experiments and the considered setups. The table shows the label of the experiment, the baseline $L$, the mean neutrino energy $\langle E_\nu \rangle$, the source power $P_{\rm Source}$ (for beams: in protons on target per year, for reactors: in gigawatts of thermal reactor power), the detector technology, the fiducial detector mass $m_{\rm Det}$, and the running time $t_{\rm run}$. Note that most results are, to a first approximation, a function of the product of running time, detector mass, and source power. Table modified from Ref [52].

of particular importance since, not only is $\theta_{13}$ the only unmeasured mixing angle, but its value will determine the prospects for determining the mass hierarchy and making a sensitive search for CP violation.

In this section we describe the expected evolution of our sensitivity to $\theta_{13}$ over the next ten to fifteen years, a time period that includes a first generation of Fermilab Proton Driver experiments. A list of relevant experiments and their characteristics is given in Table 2. The $\sin^2 2\theta_{13}$ sensitivities for these experiments are summarized in Fig 3, where the other oscillation parameters have been chosen to correspond to the present central values. Note that in general the sensitivities of the accelerator based experiments are dominated by statistical uncertainties. To make further progress will require larger detectors and higher intensity beams. Reactor-based experiments, by contrast, are dominated by systematic uncertainties.

### 2.3.1 Conventional Beam Experiments

MINOS is a muon-neutrino disappearance experiment that is expected to confirm the oscillation interpretation of the atmospheric neutrino data and to better determine the associated $|\Delta m^2|$. MINOS will also have some capability to detect electron-neutrino appearance, and hence has some sensitivity to $\theta_{13}$. However, this sensitivity is limited. MINOS is just beginning to start taking data. In the coming 5 years we expect MINOS to determine $\theta_{13}$ if it is very close to the present bound. MINOS is also expected to reduce the uncertainty on $|\Delta m^2_{31}|$ to about $\pm 10\%$.

In Europe, the CNGS program consists of two experiments, ICARUS and OPERA, designed to study tau-neutrino appearance with an L/E corresponding to the atmospheric neutrino oscillation scale. In addition, there will be sensitivity to electron-

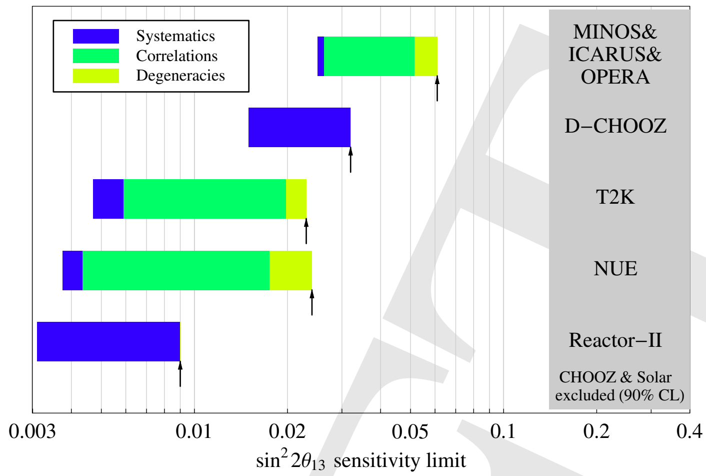


Figure 3: The $\sin^2 2\theta_{13}$ sensitivity limit at the 90% CL for MINOS, ICARUS, and OPERA combined, Double-Chooz, T2K, Reactor-II , and a NuMI Upgraded Experiment (NUE). Note that for the calculation NUE corresponds to the proposed NO$\nu$A experiment (see Table 2). The left edges of the bars are obtained for the statistics limits only, whereas the right edges are obtained after successively switching on systematics, correlations, and degeneracies, *i.e.*, they correspond to the final $\sin^2 2\theta_{13}$ sensitivity limits. The gray-shaded region corresponds to the current $\sin^2 2\theta_{13}$ bound at 90% CL. For the true values of the oscillation parameters, we use $|\Delta m^2_{31}| = 2.0 \cdot 10^{-3}\,\mathrm{eV}^2$, $\sin^2 2\theta_{23} = 1$, $\Delta m^2_{21} = 7.0 \cdot 10^{-5}\,\mathrm{eV}^2$, $\sin^2 2\theta_{12} = 0.8$ [53–56], and a normal mass hierarchy. Figure extended version from Ref. [52].

neutrino appearance, and hence to $\theta_{13}$. The CNGS experiments are expected to begin running in a few years. After 5 years of data taking, the combined sensitivity of ICARUS, OPERA, and MINOS will enable $\sin^2 2\theta_{13}$ to be determined if it exceeds $\sim 0.06$.

### 2.3.2 Off-Axis Experiments

Looking further into the future, significant progress could be made with a new long-baseline experiment that exploits the NuMI beamline, together with a Proton Driver, and a detector that is optimized to detect $\nu_e$ appearance. In the following we will refer to this generic NuMI Upgraded Experiment as NUE. There are several possible detector technology choices for NUE. There are also choices for the central beam energy and baseline, which are related to choices about whether the detector is on-axis (with respect to the central beam direction) or off-axis. In the following we have exploited the calculations available from the NO$\nu$A collaboration to obtain a quantitative understanding of the achievable sensitivity at a 2 MW Proton Driver. Hence, NUE numbers and figures in the following discussion correspond to a 50 kt detector placed about 15 mrad off-axis from the NuMI beamline, and a baseline of 812 km. Although no NuMI upgraded experiment has yet been approved, we might imagine that NO$\nu$A, or an equivalent experiment, is approved, constructed, and becomes operational in 5-10 years from now. Based on NO$\nu$A calculations, after 5 years of data taking we would expect NUE to determine $\sin^2 2\theta_{13}$ if it exceeds $\sim 0.02$.

In Japan the JPARC beamline for T2K, a high-statistics, off-axis, second gener-

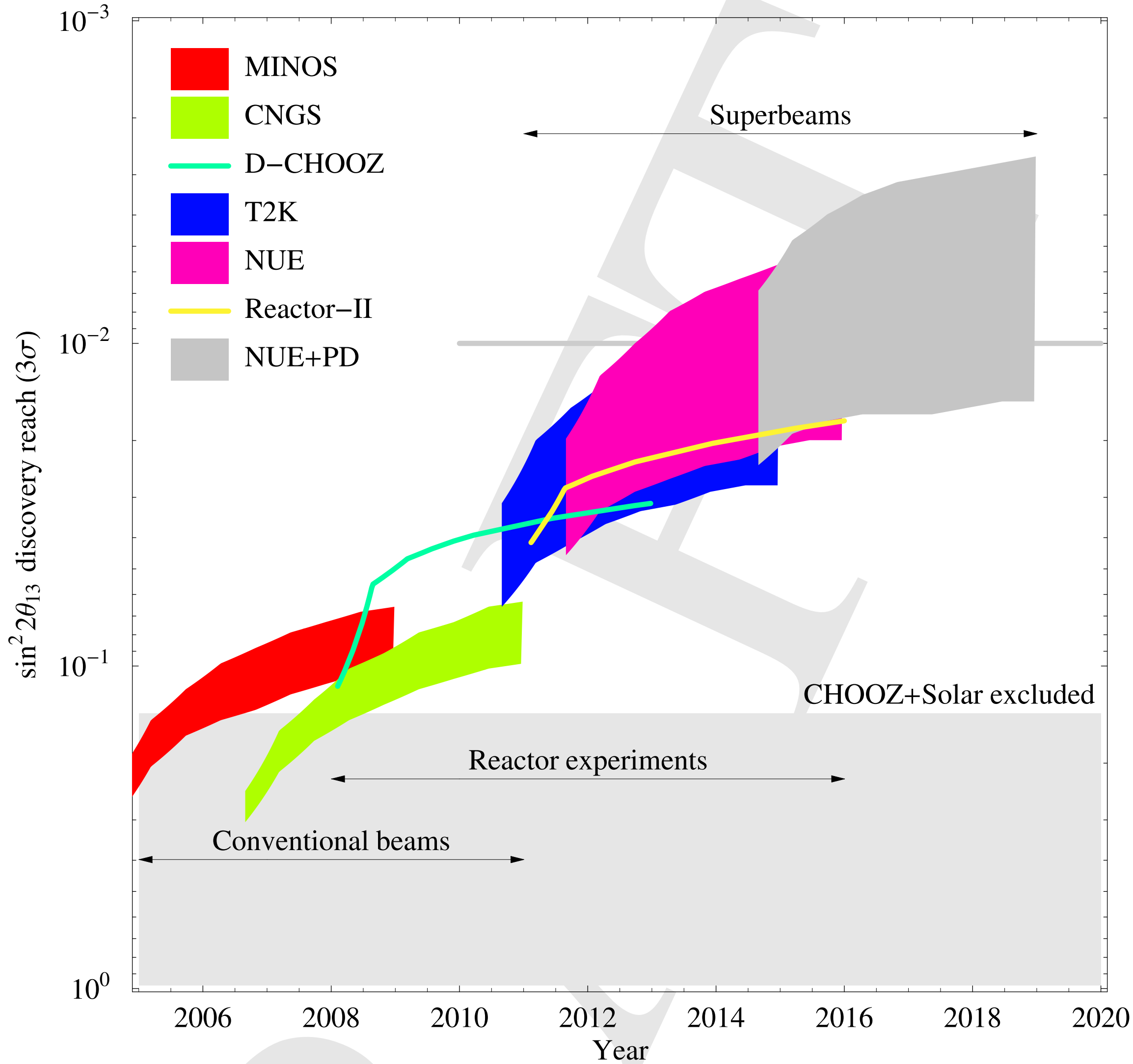


Figure 4: Anticipated evolution of the $\sin^2 2\theta_{13}$ sensitivity for the global neutrino program. The curves show the $3\sigma$ sensitivities for each experiment to observe a non-zero value of $\sin^2 2\theta_{13}$. The bands reflect the dependence of the sensitivity on the CP violating phase $\delta$. The calculations are based on the experiment simulations in Refs. [52, 57] and include statistical and systematic uncertainties and parameter correlations. They assume a normal hierarchy and $\Delta m^2_{31} = 2.5 \cdot 10^{-3}\,\mathrm{eV}^2$, $\sin^2 2\theta_{23} = 1$, $\Delta m^2_{21} = 8.2 \cdot 10^{-5}\,\mathrm{eV}^2$, $\sin^2 2\theta_{12} = 0.83$. All experiments are operated with neutrino running only and the full detector mass is assumed to be available right from the beginning. The starting times of the experiments have been chosen as close as possible to those stated in the respective LOIs. The NUE numbers correspond to NO$\nu$A.

ation version of K2K, has been approved, and is expected to be completed in 2009. With 5 years of data taking T2K is expected to determine $\sin^2 2\theta_{13}$ if it exceeds $\sim 0.02$. The combined NUE and T2K sensitivity would be in the range 0.01-0.02.

### 2.3.3 Reactor Experiments

A new generation of reactor experiments are being proposed with detectors and baselines chosen to be sensitive to $\theta_{13}$. Although choices still have to be made to determine which of these experiments are supported, it seems reasonable to assume that one or two reactor experiments will be executed in the coming decade. The Double-CHOOZ experiment appears to be furthest along in the approval process. This experiment is expected to determine $\sin^2 2\theta_{13}$ if it exceeds $\sim 0.03$. Beyond this, a more ambitious reactor experiment, referred to in Table 2 as Reactor II, might be expected to reach a sensitivity $\sin^2 2\theta_{13}$ approaching 0.01. This sensitivity is limited by systematic uncertainties but, if achieved, will be slightly better than the corresponding sensitivity expected for T2K, and might be obtained on a similar timescale.

### 2.3.4 The Evolution

The anticipated evolution of the $\sin^2 2\theta_{13}$ sensitivity of the global neutrino oscillation program is illustrated in Fig. 4. The sensitivity is expected to improve by about an order of magnitude over the next decade. This progress is expected to be accomplished in several steps, each yielding a factor of a few increased sensitivity. During this first decade the Fermilab program will have contributed to the improving global sensitivity with MINOS, followed by NUE. MINOS is the on-ramp for the US long-baseline neutrino oscillation program. NUE would be the next step. Note that we assume that NUE starts taking data with the existing beamline before the Proton Driver era. The Proton Driver would take NUE into the fast lane of the global program. Also note that the accelerator based and reactor based experiments are complementary. In particular, the reactor experiments make disappearance measurements, limited by systematic uncertainties. The NUE experiment is an appearance experiment, limited by statistical uncertainties, and probes regions of parameter space beyond the reach of the proposed reactor experiments.

## 2.4 Fermilab Proton Driver Oscillation Physics Program

Independent of the value of $\theta_{13}$ the initial Fermilab Proton Driver long-baseline neutrino experiment (NUE) is expected to make an important contribution to the global oscillation program. If $\theta_{13}$ is very small NUE would be expected to provide the most stringent limit on this important parameter, and prepare the way for a neutrino factory. If $\theta_{13}$ is sufficiently large, NUE would be expected to measure its value, perhaps determine the mass hierarchy, and prepare the way for a sensitive search for CP violation. The evolution of the Fermilab Proton Driver physics program beyond the initial experiments will depend not only on $\theta_{13}$, but also on what other neutrino experiments will be built elsewhere in the world. In considering the long-term evolution of the Fermilab Proton Driver program we must take into account the uncertainty on the magnitude of $\theta_{13}$ and consider how the global program might evolve.

We begin by considering the evolution of the program if $\sin^2 2\theta_{13} < 0.01$. In this case we will know that ultimately we will need a neutrino factory to complete all of the

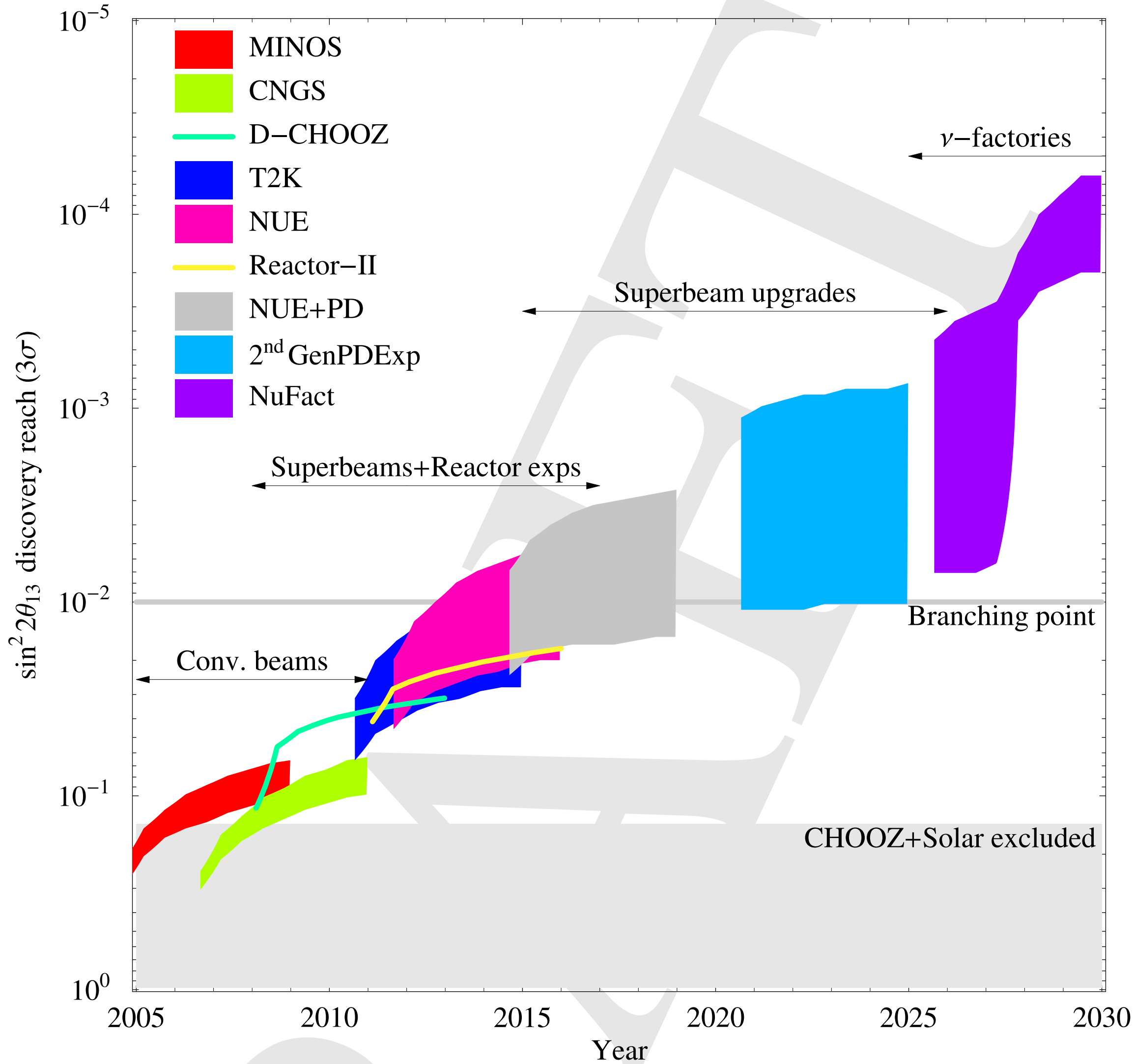


Figure 5: Anticipated evolution of the $\sin^2 2\theta_{13}$ sensitivity for the global neutrino program. See caption for Fig 4 for details. The "branching point" refers to the decision point for the experimental program (rather than the Fermilab Proton Driver), *i.e.*, between an upgraded beam and/or detector and a neutrino factory program. The upgrade 2ndGenPDExp (Second Generation Proton Driver Experiment) is assumed to start ten years after T2K starts and the curve uses numbers from the T2HK proposal. The neutrino factory is assumed to start about ten years after the branching point and to switch polarity after 2.5 years.

important oscillation measurements. The initial Fermilab Proton Driver experiment would be a search experiment that would improve the limit on, or establish the value of, $\theta_{13}$ and prepare the way for a neutrino factory. Figure 5 shows a longer-term version of the $\sin^2 2\theta_{13}$ sensitivity versus time plots shown in Fig. 4. The initial Fermilab Proton Driver experiment would begin to explore the region below $\sin^2 2\theta_{13} \sim 0.01$

and could be upgraded to further improve the sensitivity by a factor of a few. The neutrino factory would ultimately provide a two orders of magnitude improvement in sensitivity.

We have no reason to expect a very small value for $\theta_{13}$. Hence, as the global program achieves increasing sensitivity to $\theta_{13}$, at any time a finite value might be established, and the focus of the program will change from searching for evidence for $\nu_\mu \leftrightarrow \nu_e$ transitions to measuring $\theta_{13}$, determining the mass hierarchy, and searching for CP violation. To explore how in this case the Fermilab Proton Driver would contribute to the global program we consider four cases:

**Case 1:** No Fermilab Proton Driver and no upgrade to the JPARC beam.

**Case 2:** An upgrade to the JPARC beam, but no Fermilab Proton Driver.

**Case 3:** A Fermilab Proton Driver, but no upgrade to the JPARC beam.

**Case 4:** Both a Fermilab Proton Driver and an upgraded JPARC beam.

| Name | Detector Mass (kton) | Proton Power (MW) | Running Time (years) |
|---|---|---|---|
| NUE | 50 | 0.4 | $3\nu + 3\bar{\nu}$ |
| PD+NUE | 50 | 2.0 | $3\nu + 3\bar{\nu}$ |
| PD+NUE+$2^{nd}$ NUE | 50(+50) | 2 | 6 (3)$\nu$ + 6 (3) $\bar{\nu}$ |
| PD+Long Baseline | 125 or 500 | 2 + 2 | $5\nu + 5\bar{\nu}$ |
| T2K | 50 | 0.77 | $3\nu + 3\bar{\nu}$ |
| T2K* | 50 | 4 | $3\nu + 3\bar{\nu}$ |
| T2HK | 500 | 4 | $3\nu + 3\bar{\nu}$ |
| $\nu$ Factory | 50 | 4 | $3\nu + 3\bar{\nu}$ |

Table 3: Summary of the various experiments which are described in the previous chapters. NUE numbers are for the proposed NO$\nu$A detector.

The prospects for determining the neutrino mass hierarchy and discovering CP violation depend upon the values of $\theta_{13}$ and $\delta$. Figures. 6,7, 8 and 9 show as a function of $\sin^2 2\theta_{13}$, for various combinations of experiments, the fraction of all possible values of $\delta$ for which the mass hierarchy can be determined (left panels) and CP violation can be discovered (right panels).

The first case, where there is no Fermilab Proton Driver and no upgrade to the JPARC beam, is shown in Figure 6. Note that even by combining T2K and NUE data, one cannot arrive at a $3\sigma$ determination for CP violation. If, in addition to no Fermilab Proton Driver, there is no NUE then T2K alone will not be able to determine the mass hierarchy. NUE would provide some sensitivity to the mass hierarchy, which would be somewhat improved by combining NUE and T2K results.

The second case, where there is no Fermilab Proton Driver but the JPARC beam is upgraded, is shown in Figure 7. We assume that NUE is built, which will provide some sensitivity to the mass hierarchy. In this case, there is some parameter space where CP violation can be seen at $3\sigma$, which expands dramatically if there is a 20-fold increase in detector mass which would happen if Hyper-Kamiokande were to be built. However, there would always be a significant fraction of $\delta$ for which there would be an ambiguity due to the uncertain mass hierarchy, which means that a degenerate CP conserving solution may overlap the CP violating solution and destroy the CP violation sensitivity. The JPARC upgrades would also extend the sensitivity to the mass hierarchy. However, because the baseline is 295 km, these substantial upgrades make only a modest impact on the mass hierarchy sensitivity for a limited fraction of the $\delta$ parameter space.

The third case, shown in figure 8, is where there is a Fermilab Proton Driver, but no JPARC upgrade The curves show various options: either running with one or more detectors located at different off axis angles from the NuMI beamline, or with a new long baseline experiment with a new beamline. Note that the Fermilab Proton Driver yields a dramatic improvement in the potential to determine the mass hierarchy, which compares favorably with Case 2. The initial Fermilab Proton Driver experiment would have limited sensitivity to CP violation, but further upgrades to the beamline and detector would provide a significantly improved sensitivity which is again favorable when compared to Case 2.

The fourth case, shown in figure 9, is where there is a both a Fermilab Proton Driver and an upgraded JPARC program. If in the initial program the detectors are not upgraded then there is some improvement in sensitivity over Case 3, particularly for the mass hierarchy at large $\sin^2 2\theta_{13}$. However, as detectors are upgraded, the ultimate sensitivities are comparable to those of Case 3.

In presenting the impact of a Fermilab Proton Driver on the global neutrino program we have featured an off-axis narrow band beam experiment, NUE. Recently a group from Brookhaven have proposed an alternative approach which exploits an on-axis broad band beam with a long baseline (L = 2540 km corresponding to BNL to the Homestake mine). To understand whether this approach could also be implemented at Fermilab calculations have been made [58] for a baseline of 1290 km, corresponding to FNAL to the Homestake mine. The resulting precision in the $(\sin^2 2\theta_{13}, \delta)$ plane is found to be comparable to or better than the L = 2540 km case. Whether the broadband beam concept is better or worse than the off-axis concept depends critically on the assumed background levels for the broadband experiment. A third alternative has been proposed in which a broad energy range is covered by a set of narrow band beams going to the same detector, the tighter energy spread significantly reducing backgrounds. One of these neutrino beams would be produced using the 8 GeV linac beam, and would require the highest practical primary beam power ($\sim 2$ megawatts). Whichever is ultimately preferred, the Fermilab Proton Driver would be able to accommodate any of these alternatives.

In summary, although we do not know the value of $\theta_{13}$ or at what point in time its value will be known, we do know that the Fermilab Proton Driver will offer choices that will enable it to provide a critical contribution to the global program. In all the cases considered, without a Fermilab Proton Driver the sensitivity to the neutrino mass hierarchy will be very limited.

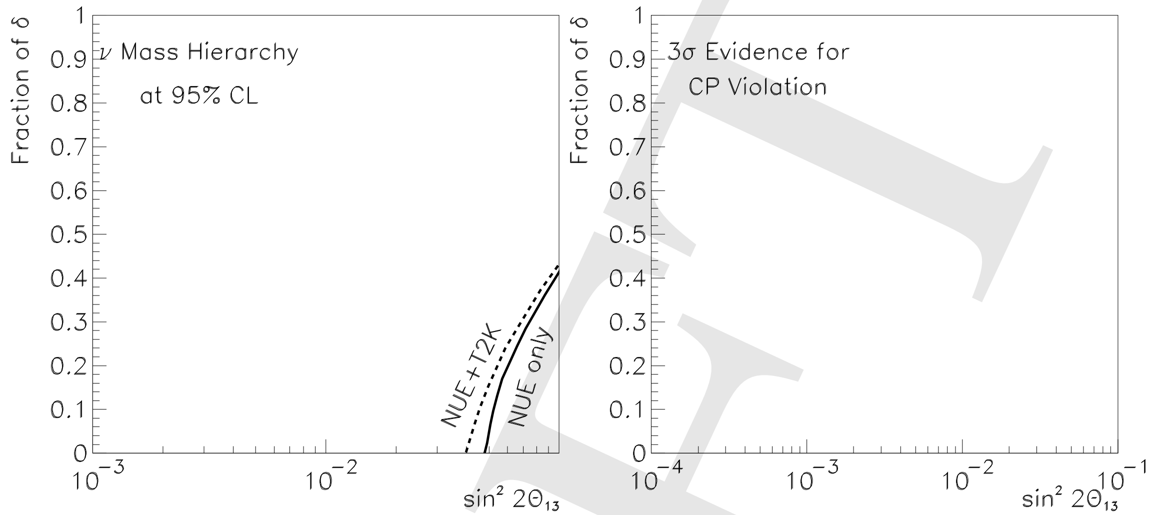


Figure 6: **Case 1:** Regions of parameter space where the mass hierarchy (left) and CP violation (right) can be observed at 95% CL and at $3\sigma$, respectively. Note that CP violation would not be visible at all and T2K alone is not sensitive to the hierarchy. NUE, T2K, etc are defined in Table 3.

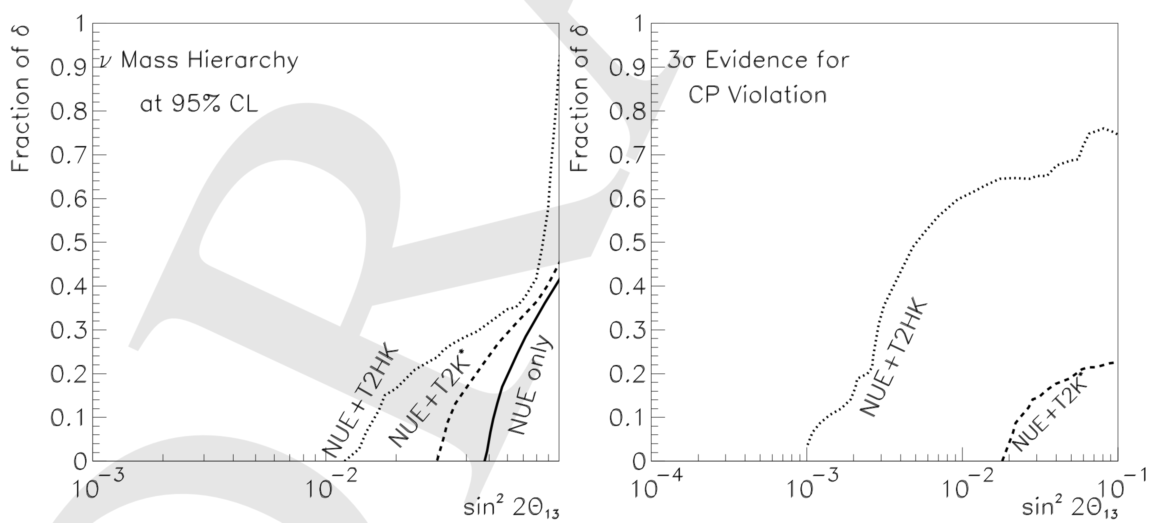


Figure 7: **Case 2:** Regions of parameter space where the mass hierarchy (left) and CP violation (right) can be observed at 95% CL and at $3\sigma$, respectively. NUE, T2K, etc are defined in Table 3.

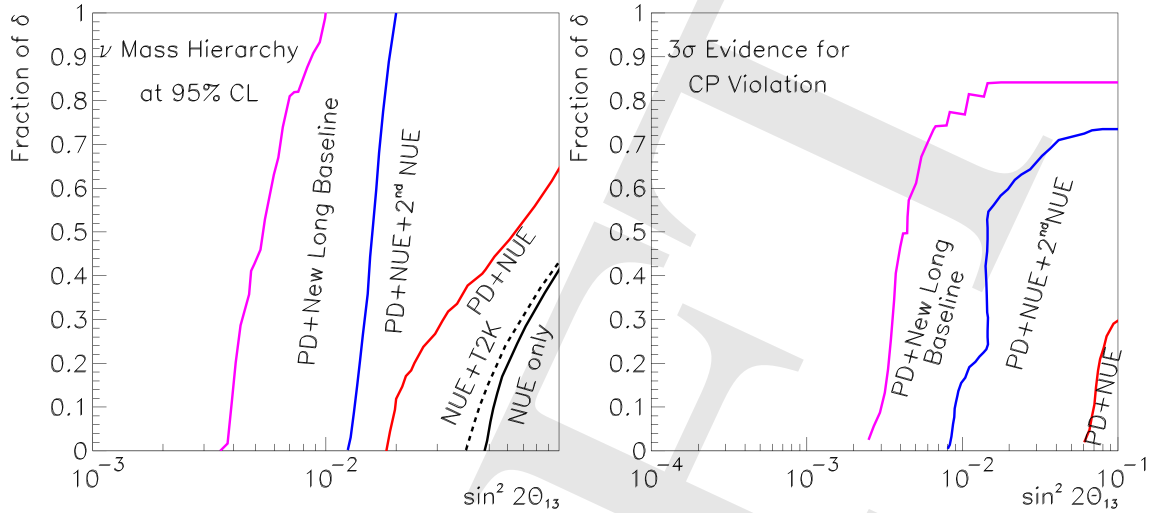


Figure 8: **Case 3:** Regions of parameter space where the mass hierarchy (left) and CP violation (right) can be observed at 95% CL and at $3\sigma$, respectively. NUE, T2K, etc are defined in Table 3.

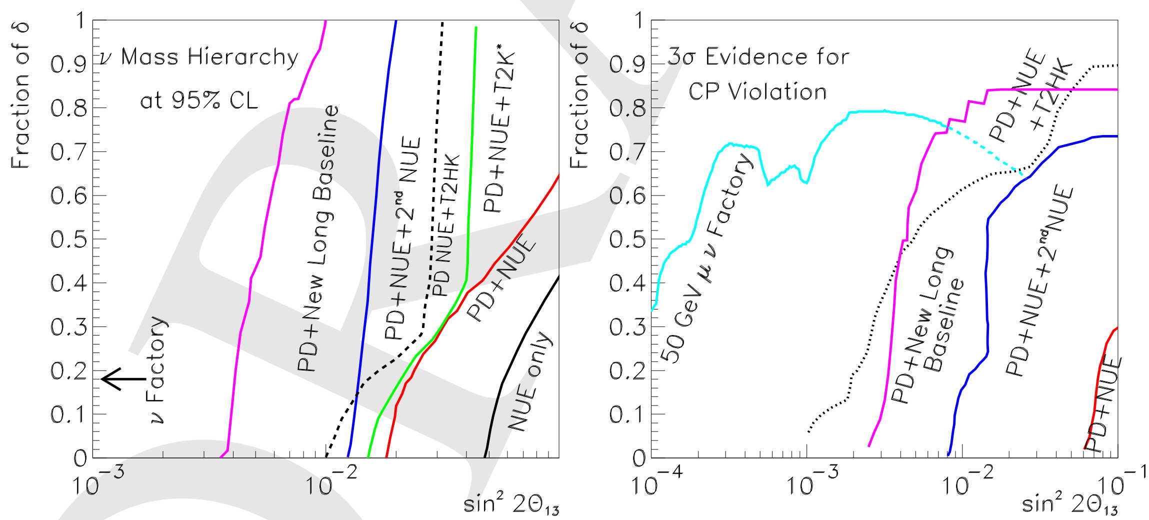


Figure 9: **Case 4:** Regions of parameter space where the mass hierarchy (left) and CP violation (right) can be observed at 95% CL and at $3\sigma$, respectively. NUE, T2K, etc are defined in Table 3.

## 2.5 Neutrino Scattering Physics Program

Neutrino and antineutrino scattering measurements are of interest for a variety of reasons. Charged Current (CC) Quasi-Elastic (QE) scattering probes the structure of the nucleon and the binding of nucleons within the nucleus. Neutral Current (NC) elastic scattering probes the strange quark contribution to the spin structure of the nucleon. Resonance production and the transition region to deeply inelastic scattering (DIS) provides tests of non-perturbative QCD. The study of nuclear effects with neutrino interactions permits the determination of quark-flavor dependent nuclear effects and a better understanding of the role of coherence length in nuclear shadowing. Strange particle production measurements are needed to better understand backgrounds important in proton decay searches, and neutrino-electron elastic scattering can be used to search for physics beyond the Standard Model. In more detail:

(i) **Parton Distribution Functions** The study of the partonic structure of the nucleon, using the neutrino's weak probe, could complement the on-going study of this subject with electromagnetic probes at Jlab. The unique ability of the neutrino to "taste" only particular flavors of quarks enhances any study of parton distribution functions.

With the high statistics foreseen with the Fermilab proton driver as well as the special attention to minimizing neutrino beam systematics, it should be possible for the first time to determine the separate structure functions $2F_1^{\nu N}(x,Q^2)$, $2F_1^{\bar{\nu} N}(x,Q^2)$, $F_3^{\nu N}(x,Q^2)$ and $F_3^{\bar{\nu} N}(x,Q^2)$ where N is an isoscalar target. In leading order QCD (used for illustrative purposes) these four structure functions are related to the parton distribution functions by:

$$
\begin{aligned}
2F_1^{\nu N}(x,Q^2) &= u(x)+d(x)+s(x)+\bar{u}(x)+\bar{d}(x)+\bar{c}(x)\\
2F_1^{\bar{\nu} N}(x,Q^2) &= u(x)+d(x)+c(x)+\bar{u}(x)+\bar{d}(x)+\bar{s}(x)\\
xF_3^{\nu N}(x,Q^2) &= u(x)+d(x)+s(x)-\bar{u}(x)-\bar{d}(x)-\bar{c}(x)\\
xF_3^{\bar{\nu} N}(x,Q^2) &= u(x)+d(x)+c(x)-\bar{u}(x)-\bar{d}(x)-\bar{s}(x)
\end{aligned}
$$

Note that taking differences and sums of these structure functions would then allow extraction of individual parton distribution functions in a given $x, Q^2$ bin:

$$
\begin{aligned}
2F_1^{\nu N}-2F_1^{\bar{\nu} N} &= [s(x)-\bar{s}(x)]+[\bar{c}(x)-c(x)]\\
2F_1^{\nu N}-xF_3^{\nu N} &= 2[\bar{u}(x)+\bar{d}(x)+\bar{c}(x)]\\
2F_1^{\bar{\nu} N}-xF_3^{\bar{\nu} N} &= 2[\bar{u}(x)+\bar{d}(x)+\bar{s}(x)]\\
xF_3^{\nu N}-xF_3^{\bar{\nu} N} &= [\bar{s}(x)+s(x)]-[\bar{c}(x)+c(x)]
\end{aligned}
$$

Our knowledge of the the parton distributions is still very incomplete. For example, although we know that the net number of strange quarks is zero, there is no reason for $s(x) = \bar{s}(x)$. A global analysis to determine the strange sea asymmetry as a function of $x$ shows moderate deviations from zero at higher $Q^2$. Differences between $s$ and $\bar{s}$ can have a significant impact on the extraction of $\sin^2\theta_W$ from $\nu, \bar{\nu}$ data [59]. Even the valence PDFs are not well known at large $x$. The ratio of $d/u$ is normally determined by comparing scattering from the proton and neutron. However, because no free neutron target exists, the deuteron is used as a neutron target. Although this makes little difference in the extracted value at small $x$, uncertainties in the nuclear corrections become substantial for $x$ larger than about 0.6, and make determination of the ratio essentially impossible for $x$ larger than about 0.8, as shown in Fig. 10. The ratio

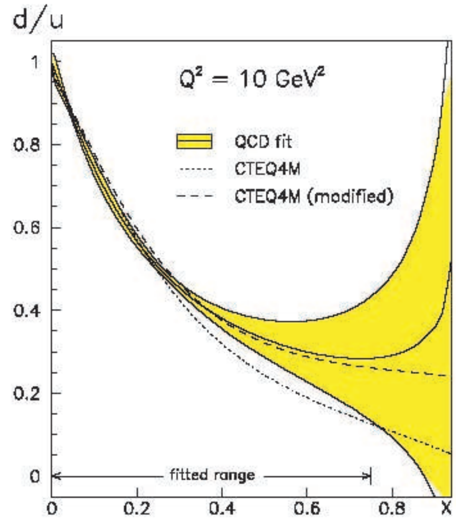


Figure 10: The $d/u$ ratio showing the uncertainty due to nuclear effects in the deuteron. Figure taken from Ref. [60].

of $d/u$ can be determined without any nuclear structure effect corrections by using neutrino and antineutrino scattering on hydrogen, as the ratio $F_2^{\nu p}/F_2^{\bar{\nu} p}$ is equal to $d/u$. Hence, a MW-scale Proton Driver would enable progress in obtaining a more complete knowledge of the parton distributions within the nucleon.

With the proposed Fermilab Proton Driver, the expected POT per year is expected to be at least 20x$10^{20}$. As will be summarized shortly, the expected number of DIS events per ton of detector would be (units of 1 K events): ME - 2170, HE - 5100, $\bar{ME}$ - 565, $\bar{HE}$ - 1210. Note that without the Proton Driver, the statistics for the $\bar{\nu}$ case would be reduced by a factor of 5 necessitating multi-year exposures to accumulate sufficient statistics at high $x$.

(ii) **Generalized Parton Distribution Functions** One of the most exciting developments in the theory of the structure of the nucleon has been the introduction of generalized parton distributions (GPDs) [61–65]. The usual PDFs are sensitive only to the longitudinal momentum distributions of the parton. In contrast, the elastic form factors integrate over the longitudinal distributions of the partons and describe the spatial distribution. The GPDs give a more complete picture of the nucleon in which the spatial distribution can be determined as a function of the longitudinal momentum distribution. However, the GPDs are difficult to access experimentally because they require measurement of exclusive final states. The most promising reaction to date is deeply virtual Compton scattering (DVCS), i.e. $p(e, e'\gamma p)$. These measurements are either underway or planned at JLab. However, a complete determination of the GPDs requires flavor separation which can only be accomplished using neutrinos and anti-neutrinos. Because of the requirement that exclusive final states be measured, the reaction is difficult to perform on nuclei. Although MINER$\nu$A will measure GPDs on carbon, due to nuclear effects this is considerably inferior to measurement on the proton. A true GPD measurement would require measurement of the $p(\bar{\nu}, \mu\gamma n)$ reaction using a free proton (i.e. hydrogen) target or $n(\nu, \mu\gamma p)$ reaction using a free neutron target (in practice, a deuteron target). Estimates for this "weak DVCS" process are currently being made by A. Psaker [66]. The CC cross section is of order $10^{-41}\text{cm}^2$ and the NC about 10 times smaller. These small cross sections will clearly require higher intensity neutrino beams than are available at NuMI if measurements on hydrogen are to be performed.

(iii) **Strange Quarks and the Spin Structure of the Nucleon** The NC elastic scattering of neutrinos and antineutrinos on nucleons ($\nu N \to \nu N$, $\bar{\nu} N \to \bar{\nu} N$) provides information about the spin structure of the nucleon. In particular, these scattering processes are sensitive to the isoscalar spin structure that results from strange quark contributions. Determination of the strange quark contribution to the nucleon $\Delta s$ has been a major component of the JLab program. Note that $\Delta s$, has been measured to be $\approx -0.1$ in deep-inelastic scattering (DIS) polarized lepton experiments [67]. NC elastic scattering measures the flavor non-singlet combination of all flavors. However, recent work by Bass *et al.* [68] has shown it is possible to eliminate the heavy flavor contribution. Combined with this, a precise measurement of NC elastic scattering would provide a direct measurement of $\Delta s$ that is insensitive to theoretical assumptions. The ideal measurement would be of the $(\nu p \to \nu p)/(\nu n \to \mu p)$ cross-section ratio on a deuterium target. The proposed FINeSSE experiment was designed to determine $\Delta s$ by making an accurate measurement of this cross-section ratio using the Fermilab Booster neutrino beam and a carbon target (liquid scintillator). The ultimate goal in this program requires measuring NC elastic scattering with both neutrinos and antineutrinos, with a large event sample, on *nucleon* targets, which will require a MW-scale proton source to produce a narrow band neutrino beam of high intensity.

(iv) **Neutrino-Electron Elastic Scattering and the Neutrino Magnetic Moment** The Standard Model predictions for neutrino-electron elastic scattering have little theoretical uncertainty, and a measurement of $\nu e \to \nu e$ scattering can therefore be used in principle to precisely determine $\sin^2\theta_W$, and search

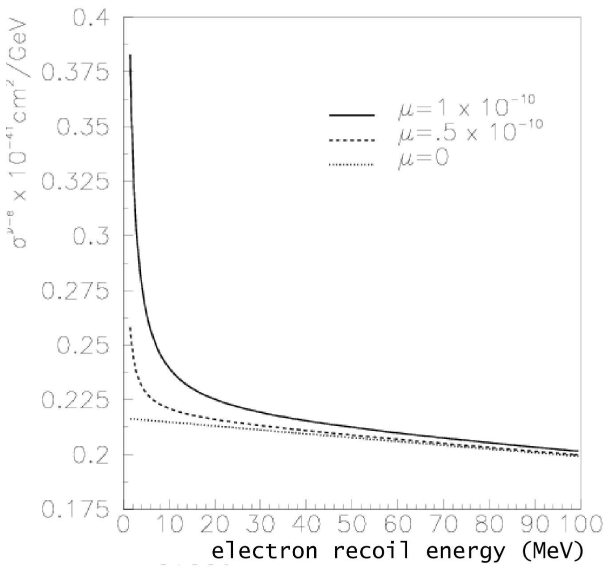


Figure 11: Differential cross section versus electron recoil kinetic energy, T, for $\nu e \rightarrow \nu e$ events. The electroweak contribution is linear in T (bottommost line), while contributions from nonzero neutrino magnetic moments yield sharp rises at low T.

for physics beyond the Standard Model. However, absolute cross-section measurements with the required precision are challenging, and may not be possible, even with a proton-driver class neutrino beam. An alternative strategy is to measure the well-predicted energy-dependent shape of the cross section. This would enable a search for physics beyond the Standard Model. As an example, consider a search for a finite neutrino magnetic moment, which is theoretically possible since we now know that neutrinos have finite masses. Within the Standard Model, modified to include finite neutrino masses, neutrinos may acquire a magnetic moment via radiative corrections. With $m_\nu = 1$ eV, the resulting magnetic moment would be $\approx 3 \times 10^{-19} \mu_B$ where $\mu_B = e/2m_e$ is the Bohr magneton. This value is too small to be detected or to affect astrophysical processes. Hence, a search for a finite neutrino magnetic moment is a search for physics beyond the Standard Model. The current best limit on the muon neutrino magnetic moment is $\mu_{\nu_\mu} \leq 6.8 \times 10^{-10} \mu_B$ from LSND $\nu_\mu e$ elastic scattering [69]. This sensitivity may be substantially improved, perhaps to the level of some beyond-the- Standard-Model predictions (which in some cases are as large as $10^{-11} \mu_B$ ), by precisely measuring the elastic scattering rate as a function of electron recoil energy. An electromagnetic contribution to the cross section from the magnetic moment will show up as an increase in event rate at low electron recoil energies (see Figure 11). The needed sensitivity requires a MW-class Proton Driver to produce a sufficiently intense neutrino beam, and a precise tracking detector with a low electron energy threshold. Depending on the energy threshold, a gain of 10-30 over the LSND measurement is possible.

(v) **Elastic Form Factors** The distributions of charge and magnetism within the nucleus can be parameterized using two elastic form factors: the electric form factor $G_E$ and the magnetic form factor $G_M$. For many years it was assumed that both the charge and magnetic distributions fall exponentially. With this assumption it can be shown that $G_E$ and $G_M$ are described by the "dipole" form. However, precision measurements at JLab [70, 71] have shown that this is not the case; the electric form factor has a distinctly different form, and drops more quickly than the magnetic form factor (Fig. 12), indicating that the charge distribution has a broader spatial distribution than the distribution of magnetism. In the language of particle physics, Perturbative QCD predicts that

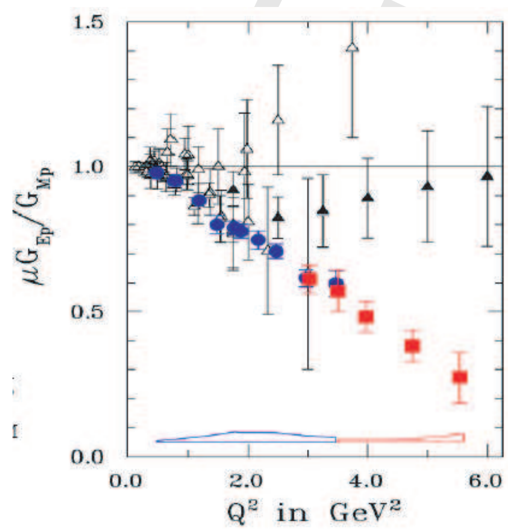


Figure 12: Ratio of the electric to magnetic form factor measured using polarization transfer. Data taken from Ref. [71].

the ratio $Q^2F_1/F_2$ should be constant. Instead it appears $QF_1/F_2$ approaches a constant. Although the reason for this is not understood, it does appear to be an indication of angular momentum between the quarks. To understand this more deeply it is desirable to precisely measure the weak form factor. This can be measured through parity violation in electron-nucleon scattering, with limited precision. Neutrino-nucleon elastic (or quasi-elastic) scattering depends on both the electromagnetic form factors and the weak form factor. Nearly half the cross section is due to the weak form factor, making neutrino-nucleon scattering a good probe. Proposed measurements of the weak form factor (e.g. the MINER$\nu$A experiment) use scattering from nucleons in nuclei. Although the statistical precision will be reasonably good, there is an uncertainty in both extracting the form factor from scattering from a bound nucleon due to final state interactions and other conventional effects, as well as the possibility of modification of the form factor by the nuclear medium. Thus, measurement of the form factor using neutrino scattering on hydrogen and deuterium is essential. This will require the intensity available at a MW-scale Proton Driver.

(vi) **Duality and Resonance Production** Although QCD appears to provide a good description of the strong interaction, we have a very poor understanding of the transition from the domain where quarks and gluons are the appropriate degrees of freedom to the domain best described using baryons and mesons. In the region of modest $Q^2$ (1-10 GeV$^2$) the scattering of electrons on nucleons is dominated by resonance production, and can also be described using the same formalism as DIS. However, there is no obvious reason to expect the structure functions measured in the resonance region from correlated partons forming the nucleon should be related to the DIS structure functions. Despite this, experiments at JLab [72] have found that the $F_2$ structure function measured in the resonance region closely follows that measured in the DIS region. The phenomenon, called quark-hadron duality, has also been observed in other processes, such as $e^+e-$ annihilation into hadrons. The origins of duality are not well understood [73–80]. However, as discussed in Ref. [81], duality does appear to be a general feature of QCD. Duality is expected to exist for neutrino scattering, although it may manifest itself quite differently than for electron scattering. Of particular interest would be a measurement of the ratio of neutron to proton neutrino structure functions as large $x$, where similar valence quark dynamics as in charged lepton scattering are probed, but with different sensitivity to quark flavors. An uncertain aspect of duality is the relationship be resonant and non-resonant backgrounds in the onset of duality. Neutrino and antineutrino scattering would provide an important consistency check as well as additional information on this aspect of duality because of the dramatically different resonance production response of the nucleon for neutrino and electron scattering. The next decade of experiments, especially with MINER$\nu$A, should provide some information on the validity of duality using neutrinos. However, high precision measurements using anti-neutrinos and nucleon (hydrogen and deuterium) targets will be required in order to fully explore the origins of duality.

(vii) **Strange Particle Production** Measurements of the production of strange mesons and hyperons in neutrino NC and CC processes (e.g. $\nu_\mu n \to \mu^- K^+ \Lambda^0$ and $\nu_\mu p \to \nu_\mu K^+ \Lambda^0$) provide input to test the theoretical models of neutrino induced strangeness production [82,83]. In addition, neutrino induced strangeness production is a significant background in searches for proton decay based on the SUSY-inspired proton decay mode $p \to \nu \Lambda K^+$. The existing experimental data on these channels consists of only a handful of events from bubble chamber experiments. There are plans to measure these reactions using the existing K2K data and the future MINER$\nu$A data. MINER$\nu$A will collect a large sample ($\approx 10,000$) of fully constrained $\nu_\mu n \to \mu^- K^+ \Lambda^0$ events. However, the antineutrino measurements will require a more intense (MW-scale) proton source.

## 2.6 Expected Event Rates with the Fermilab Proton Driver

With the Fermilab Proton Driver we expect order 20x$10^{20}$ PoT per year.

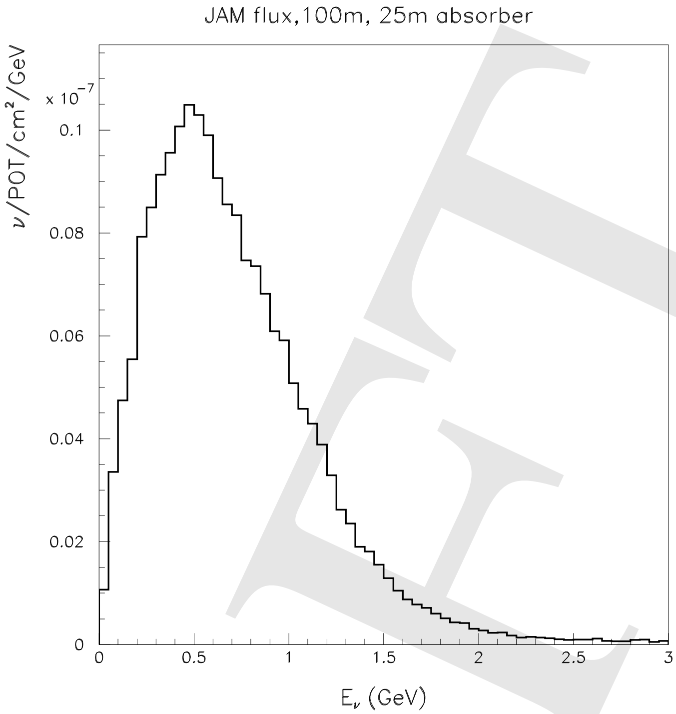


Figure 13: Calculated $\nu_\mu$ flux at a 100m location on the booster neutrino beamline.

| CC Events/$10^{20}$ PoT/ton | | | |
|---|---|---|---|
| Beam | CC $\nu_\mu$ | CC $\bar{\nu}_{mu}$ | $\nu$ in $\bar{\nu}$ beam |
| LE | 60 K | 20 K | 26 K |
| ME | 230 K | 60 K | 10.7 K |
| HE | 525 K | 125 K | 18.6 K |

Table 4: NuMI charged-current interactions per ton, per $10^{20}$ protons on target.

## 2.7 The Need for a High Intensity Proton Beam at 8 GeV

The Fermilab long-baseline neutrino oscillation program utilizes the NUMI beamline, and hence protons at MI energies. It is important to stress that the desired neutrino scattering program at a MW-class proton driver would utilize both the upgraded MI beam and the high-intensity lower energy proton beam at 8 GeV. The measurements using high-intensity neutrino and antineutrino beams of mean energy $\approx$ 1 GeV are particularly important. These measurements require that the beam have no high-energy tail (above $\approx$ 2 GeV) so that backgrounds from multipion and deep-inelastic scattering processes do not overwhelm the signal reactions of interest. The energy distribution of the booster neutrino beam, currently in operation at Fermilab, is ideal for these studies (Fig. 13). An 8 GeV MW-class proton-driver beam that uses a MiniBooNE-like horn-focusing system would satisfy the beam requirements. A 2 MW beam at 8 GeV would enable a 64-fold increase in intensity with respect to

| Event Rates per ton | | | | | | |
|---|---|---|---|---|---|---|
| CC Process | LE | ME | HE | $\bar{L}E$ | $\bar{M}E$ | $\bar{H}E$ |
| Quasi-Elastic | 6.6 K | 22.8 K | 46.2 K | 2.8 K | 7.6 K | 14.0 K |
| Resonance | 12.5 K | 43.2 K | 93.0 K | 3.3 K | 8.9 K | 17.5 K |
| Transition | 13.2 K | 53.1 K | 125.5 K | 4.5 K | 14.1 K | 30.5 K |
| DIS | 27,1 K | 108.6 K | 255.1 K | 9.0 K | 28.2 K | 60.5 K |
| Coherent | 0.6 K | 2.3 K | 5.2 K | 0.4 K | 1.2 K | 2.5 K |

Table 5: NuMI CC samples per $10^{20}$ PoT - ton for various processes.

MiniBooNE. This is the rough factor required to enable precision neutrino and antineutrino measurements using nucleon targets. In addition to the highest intensities practical, it is also important for the neutrino beam to have a very low duty-factor. This will require a buncher using either the recycler ring or a new dedicated storage ring. Note that beam-unrelated cosmic-ray-induced backgrounds increase with the duty-factor. Many of the desired neutrino measurements require low backgrounds for low energy final states (e.g. NC elastic scattering and neutrino-electron elastic scattering). These measurements would be limited with a high duty-factor neutrino beam.

# 3 The Broader Proton Driver Physics Program

In the past high precision measurements at low energies have complemented the experimental program at the energy frontier. These low energy experiments not only probe mass scales that are often beyond the reach of colliders, but also provide complementary information at mass scales within reach of the energy frontier experiments. Examples of low energy experiments that have played an important role in this way are muon g-2 measurements, searches for muon and kaon decays beyond those predicted by the Standard Model, measurements of rare kaon processes, etc. A summary of the sensitivity achieved by a selection of these experiments is given in Fig. 14. It seems likely that these types of experiment will continue to have a critical role as the energy frontier moves into the LHC era. In particular, if the LHC discovers new physics beyond the Standard Model, the measurement of quantum corrections that manifest themselves in low energy experiments would be expected to help elucidate the nature of the new physics. If no new physics is discovered at the LHC then precision low energy experiments may provide the only practical way of advancing the energy frontier beyond the LHC in the foreseeable future.

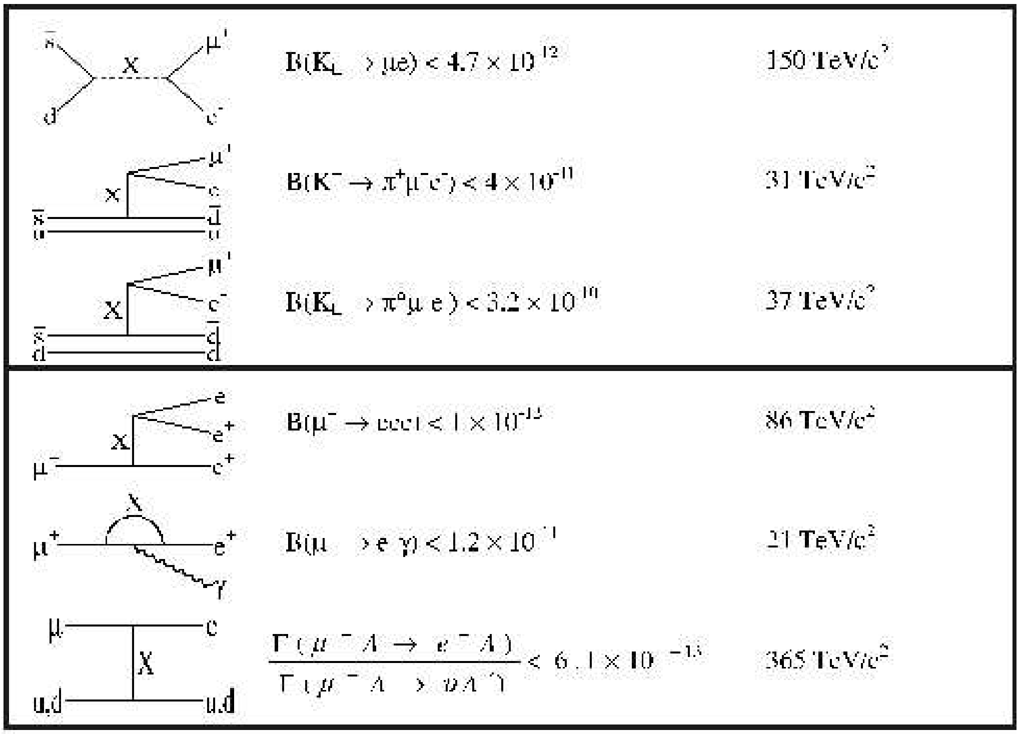


Figure 14: Current limit on Lepton Flavor Violating processes and the mass scales probed by each process. The upper box is for kaon decays, which involve a change of both quark flavor and lepton flavor. The bottom box is for muon decays, which involve only lepton flavor change. The lower limit on the mass scale is calculated assuming the electroweak coupling strength.

## 3.1 Muon Physics

Solar-, atmospheric-, and reactor-neutrino experiments have established Lepton Flavor Violation (LFV) in the neutrino sector, which suggests the existence of LFV processes at high mass scales. Depending on its nature, this new physics might also produce observable effects in rare muon processes. Furthermore, CP Violation in the charged lepton sector, revealed for example by the observation of a finite muon Electric Dipole Moment (EDM), might be part of a broader Baryogenesis via Leptogenesis picture. Hence, the neutrino oscillation discovery enhances the motivation for a continuing program of precision muon experiments. In addition, the expectation that there is new physics at the TeV scale also motivates a new round of precision muon experiments. LFV muon decays and the muon anomalous magnetic moment

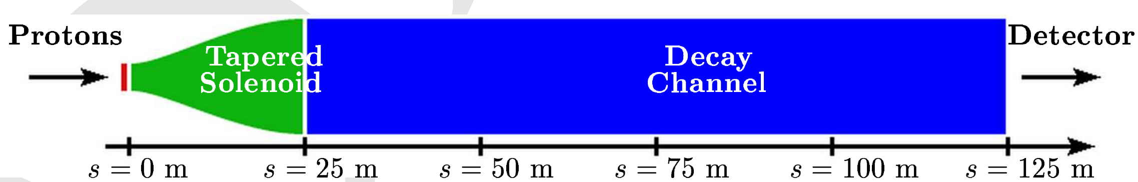


Figure 15: Schematic of the solenoid-based muon source discussed in the text. This performance of this channel has been simulated using the MARS code.

| Experiment | | $I_0/I_m$ | $\delta T$ [ns] | $\Delta T$ [$\mu$s] | $p_\mu$ [MeV] | $\Delta p_\mu/p_\mu$ [%] |
|---|---|---|---|---|---|---|
| $\mu A \to eA$ | $10^{21}$ | $< 10^{-10}$ | < 100 | > 1 | < 80 | < 5 |
| $\mu \to e\gamma$ | $10^{17}$ | n/a | n/a | n/a | < 30 | < 10 |
| $\mu \to eee$ | $10^{17}$ | n/a | n/a | n/a | < 30 | < 10 |
| $\mu e \to \mu e$ | $10^{16}$ | $< 10^{-4}$ | < 1000 | > 20 | < 30 | 1...2 |
| $\tau_\mu$ | $10^{14}$ | $< 10^{-4}$ | 100 | > 20 | 30 | < 10 |
| $g_\mu$-2 | $10^{15}$ | $< 10^{-7}$ | < 50 | $> 10^3$ | 3100 | < 2 |
| EDM | $10^{16}$ | $< 10^{-6}$ | < 50 | $> 10^3$ | <1000 | < 2 |

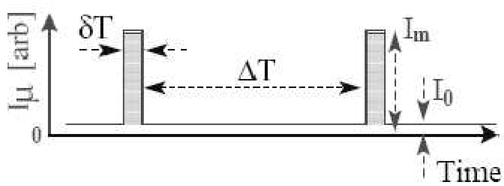


Figure 16: Beam requirements for new muon experiments. Given are the minimum total number of muons above which significant progress can be made, the muon suppression between pulses, the length and separation of pulses and the momentum spread of the muon beam.

$a_\mu = (g-2)/2$ and EDM are sensitive probes of new dynamics at the TeV scale. In general, with sufficient sensitivity, these experiments would help elucidate the nature of new physics observed at the CERN Large Hadron Collider (LHC). As an example, in SUSY models the muon (g-2) and EDM are sensitive to the diagonal elements of the slepton mixing matrix, while LFV decays are sensitive to the off-diagonal elements. If SUSY is observed at the LHC these precision muon experiments would provide one of the cleanest measurements of $\tan\beta$ and of the new CP Violating phases. It is possible that no new physics will be observed at the LHC. In this case precision muon experiments might provide, for the foreseeable future, one of the few practical ways to probe physics at higher mass scales. Note that the Brookhaven (g-2) Collaboration have reported a value for (g-2) that is 2.7 standard deviations away from the Standard Model prediction. Noting that the muon (g-2) is sensitive to any new heavy particles that couple to the muon, it is possible that the current measurements are providing an early indication of the existence of new TeV-scale particles. Higher precision measurements are well motivated.

### 3.1.1 The Muon Source

Low energy high precision muon experiments require both high intensity beams and a bunch structure that is appropriate for the experiment. Hence two ingredients needed to produce an "ideal muon source" are (i) a high intensity proton source, and (ii) a way of producing the desired bunch structure. Since different muon experiments require different bunch structures the ideal source would also be sufficiently flexible to provide different bunch structures. With an upgraded Proton Driver Fermilab would have the desired high intensity proton source. In addition, in the post-collider period it might be possible to utilize the Recycler Ring to repackage the 8 GeV proton beam, yielding the desired bunch structure. The combination of Proton Driver plus Recycler Ring would provide the front-end for a unique muon source with intensity and flexibility that exceed any existing facility.

The Recycler is an 8 GeV storage ring in the MI tunnel that can run at the same time as the MI. The Recycler is currently used for antiproton production for the Fermilab collider program. The beam from the proposed Proton Driver linac that is not used to fill the MI could be used to fill the Recycler Ring approximately ten times per second. The ring could then be emptied gradually in the 100 ms intervals between linac pulses. Extraction could be continuous or in bursts. For example, the Recycler Ring could be loaded with one linac pulse of $1.5 \times 10^{14}$ protons every 100 ms, with one missing pulse every 1.5 seconds for the 120 GeV MI program. This provides $\sim 1.4 \times 10^{22}$ protons at 8 GeV per operational year ($10^7$ seconds). In the Recycler each pulse of $1.5 \times 10^{14}$ protons can be chopped into 588 bunches of $0.25 \times 10^{12}$ protons/bunch with a pulse width of 3 ns. A fast kicker allows for the extraction of one bunch at a time. The beam structure made possible by the proton driver linac and the Recycler Ring is perfect for $\mu \to$ e conversion experiments, muon EDM searches and other muon experiments where a pulsed beam is required. Slow extraction from the Recycler Ring for $\mu \to e\gamma$ and $\mu \to 3e$ searches is also possible.

The performance of the strawman muon source shown in Fig. 15 has been simulated using the MARS code. The evolution of the pion and muon spectra down the decay channel is shown in Fig. 17 and the calculated fluxes are summarized in Table 6. The scheme will yield $\sim 0.2$ muons of each sign per incident 8 GeV proton. With $1.4 \times 10^{22}$ protons at 8 GeV per operational year this would yield $\sim 3 \times 10^{21}$ muons per year. This muon flux greatly exceeds the flux required to make progress in broad range of muon experiments (see Fig 16). However, the muons at the end of the decay channel have a large momentum spread and occupy a large transverse

| | $s = 25$ m | $s = 50$ m | $s = 75$ m | $s = 100$ m | $s = 125$ m |
|---|---|---|---|---|---|
| $\mu^+/P$ | 0.16 | 0.20 | 0.21 | 0.21 | 0.22 |
| $\mu^-/P$ | 0.16 | 0.20 | 0.21 | 0.21 | 0.21 |
| $\pi^+/P$ | 0.095 | 0.051 | 0.030 | 0.020 | 0.014 |
| $\pi^-/P$ | 0.087 | 0.044 | 0.025 | 0.016 | 0.011 |

Table 6: The number of charged particles in the beam per incident 8 GeV primary proton as a function of the distance downstream from the target. These numbers are computed using the MARS code. The normalization corresponds to a 2 MW proton driver.

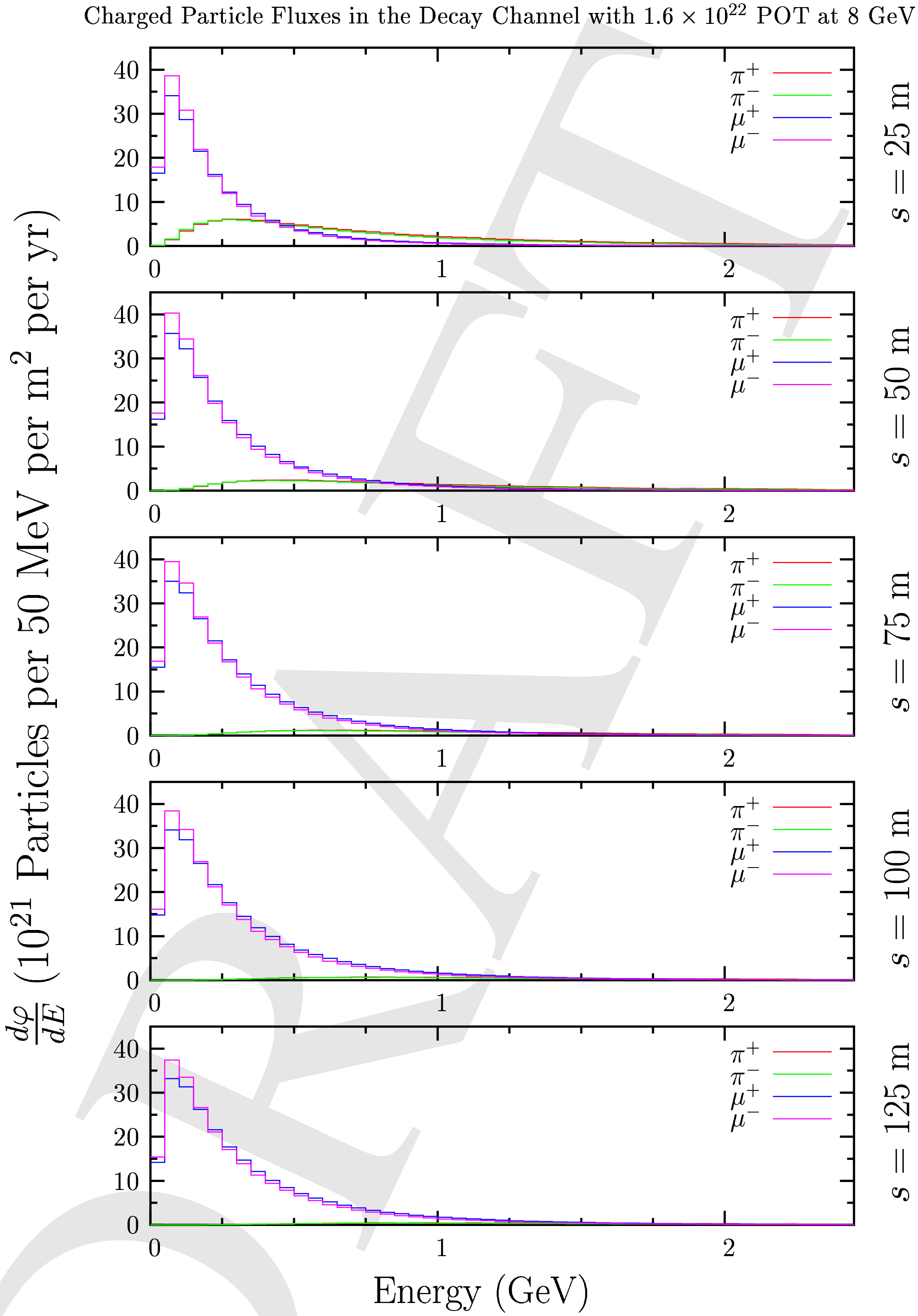


Figure 17: Charged particle fluxes at various positions down the 100 m decay channel with a 30 cm beampipe radius. The normalization corresponds to an 8 GeV, 2 MW proton driver in operation for a $10^7$-s year.

phase space. Without further manipulation their utilization will be very inefficient. The additional beam manipulating interface between the decay channel and each candidate experiment has yet to be designed. In Japan a Phase Rotated Intense Slow Muon Source (PRISM) based on an FFAG ring that reduces the muon energy spread (phase rotates) is being designed. This phase rotation ring has a very large transverse acceptance ($800\pi$ mm-mrad) and a momentum acceptance of $\pm30\%$ centered at 500 MeV/c. PRISM reduces the momentum and momentum spread to 68 MeV/c and $\pm1-2\%$ respectively. Hence, a PRISM-like ring downstream of the decay channel might accept a significant fraction of the muon spectrum (Fig. 17) and provide a relatively efficient way to use the available muon flux. Explicit design work must be done to verify this, but it should be noted that a muon selection system that utilizes only 1% of the muons available at the end of the decay channel will still produce an adequate muon flux for most of the cutting-edge experiments described in the following sections.

Finally, a new 8 GeV multi-MW Proton Driver at Fermilab, together with an appropriate target, pion capture and decay channel, would not only provide a new World Class facility for low energy muon experiments, but could also provide the first step toward a Neutrino Factory based on a muon storage ring. In the initial phase the muon beam produced in the pion decay channel would occupy a relatively large phase space. The first generation of muon experiments would use only those muons within a small part of this phase space. This muon source could then be upgraded in one or more steps with the addition of phase rotation (if not already included in the initial muon source) and cooling channels to produce a cold muon beam occupying a phase space that fits within the acceptance of an accelerator (perhaps the Proton Driver Linac). At this point the number of useful muons available for low energy muon experiments will be greatly increased. In addition, new experiments using medium energy beams of a few GeV will also become possible. Finally, the acceleration scheme would be upgraded to produce muon beams of 20 GeV or more and a muon storage ring constructed with long straight sections pointing in the desired direction. This last step would realize a Neutrino Factory, perhaps sometime within the next two decades, or on a longer timescale if a Linear Collider is constructed near Fermilab.

### 3.1.2 Electric Dipole Moment

Electric Dipole Moments violate both parity (P) and time reversal (T) invariance. If CPT conservation is assumed, a finite EDM provides unambiguous evidence for CP violation. In the Standard Model EDMs are generated only at the multi-loop level, and are predicted to be many orders of magnitude below the sensitivity of foreseeable experiments. Observation of a finite muon EDM ($d_\mu$) would therefore provide evidence for new CP Violating physics beyond the Standard Model. CP violation is an essential ingredient of almost all attempts to explain the matter-antimatter asymmetry of the Universe. However, the measured CP Violation in the quark sector is known to be insufficient to explain the observed matter-antimatter asymmetry. Searches for new sources of CP violation are therefore well motivated.

A number of extensions to the Standard Model predict new sources of CP violation. As an example, in SUSY models in which finite neutrino masses and large neutrino mixings arise from the seesaw mechanism, $d_\mu$ can be significant. If the seesaw mechanism is embedded within a left-right symmetric gauge structure the interactions responsible for the masses of right-handed Majorana neutrinos can produce values of $d_\mu$ as large as $5\times10^{-23}$ e-cm. This is well below the present limit $d_\mu < 3.7\times10^{-19}$ e-cm, but would be within reach of a new dedicated experiment at a high intensity muon source. The muon EDM group has proposed an experiment at JPARC to obtain a sensitivity of $10^{-24}$ e-cm. This sensitivity would still be limited by statistics. Higher muon intensities would help, although the measurement would also be rate limited. To obtain a sensitivity of $O(10^{-26})$ e-cm would require an improved beam structure with many short pulses, each separated by at least 500 $\mu$s. Hence, depending on the fate of the JPARC proposal, a muon EDM experiment at a Fermilab Proton Driver would be designed to obtain a sensitivity somewhere in the $10^{-24}$ - $10^{-26}$ e-cm range.

### 3.1.3 Muon g-2

The Brookhaven (g-2) Collaboration has reported a value that is 2.7 standard deviations from the Standard Model prediction. This could be an early indication of new physics at the electroweak symmetry breaking scale. Physics that would affect the value of (g-2) include muon substructure, anomalous gauge couplings, leptoquarks, and SUSY. In particular, in a minimal supersymmetric model with degenerate sparticle masses the contribution to the anomalous magnetic moment $a_\mu$ could be substantial, particularly for large $\tan\beta$. To illustrate the possibilities it is useful to consider the large $\tan\beta$ approximation with degenerate SUSY masses. The estimated range of SUSY masses that correspond to the observed $a_\mu$ are 100 - 450 GeV for $\tan\beta = 4-40$. Hence the present (g-2) experiment is probing the mass range of interest for electroweak symmetry breaking. Within the next few years, with further data taking the BNL experiment might be able to improve sensitivity by a factor of a few. To make progress beyond this will require either an upgraded storage ring or a new ring, and a higher intensity muon source. A high intensity muon source at a Fermilab Proton Driver would provide a natural home for this next generation experiment.

The current measurement of $a_\mu = (g-2)/2$ is accurate to 0.46 (stat) $\pm$ 0.27 (sys) ppm. An proposed upgrade to the current program could reduce the systematic error by a factor of 2 and increase the statistical sample by a factor of 9. This would increase the overall precision from 0.5 ppm to 0.2 ppm. Combined with expected near-term improvements in theory, this could lead to a significant confrontation with the Standard Model. A new, dedicated $g-2$ experiment could improve the overall precision by a factor of 10. This could be accomplished by reducing the systematic error by a factor of 7 and increasing the statistical sample by a factor of 200. A long list of improvements necessary to reduce the systematic error has been identified by the g-2 group. These include use of a backward muon beam, a longer pion decay beamline and better phase space matching of the beamline to the ring. Particle pile-up will ultimately limit the sensitivity of future searches. To reduce pile-up, a pulsed beam (<20 ns) with a high repetition rate and a minimum of 1 ms between pulses would be most advantageous.

### 3.1.4 Rare Muon Decays

If a negative muon is stopped in a target it will be captured by an atom and then cascade down to the 1$s$ state. In the Standard Model the muon will either decay in orbit or will be captured by the nucleus with the emission of a neutrino. In LFV models beyond the Standard Model the muon can also be converted into an electron in the field of the nucleus ($\mu \rightarrow e$ conversion) or can undergo non-Standard Model decays ($\mu \rightarrow e\gamma$, $\mu \rightarrow eee$, ...). In the Standard Model, extended to include the seesaw mechanism with right-handed neutrinos in the mass range $10^{12}$ to $10^{15}$ GeV, the predicted LFV decay branching ratios are unobservably small. However in SUSY seesaw models, parametrized at the GUT scale by the right-handed Majorana mass matrix and the neutrino Yukawa matrix, the Yukawa couplings induce off-diagonal mixing matrix elements at the one-loop level. The resulting LFV decay branching ratios can be significant. The predicted branching ratios depend upon the origin of SUSY breaking. Muon LFV decay searches therefore place constraints on SUSY breaking schemes.

Consider first $\mu \rightarrow e\gamma$. The present limit on the decay branching ratio is $1.2 \times 10^{-11}$. Within the context of SUSY models, this limit already constrains the viable region of parameter space. The MEG experiment at PSI is expected to reach a branching ratio sensitivity of $10^{-14}$ by the end of the decade. The MEG measurement will provide constraints on SUSY parameter space complementary to those obtained by the LHC experiments. If MEG observes $\mu \rightarrow e\gamma$ then both a higher statistics experiment and new searches for other non-Standard Model decay modes will be well motivated. If MEG only obtains a limit, further progress will also require a more sensitive experiment. In either case, a $\mu \rightarrow e\gamma$ experiment at a new Fermilab Proton Driver would provide a way forward provided a high sensitivity experiment can be designed to exploit higher stopped muon rates. Progress will depend upon improvements in technology to yield improved background rejection and higher rate capability. Background rejection depends upon track pointing resolution, energy resolution, and timing resolution. Fortunately, we can anticipate significant improvements in tracking technology in the next few years, and corresponding improvements in the critical detector resolutions and rate capability. To illustrate the possible gains in the $\mu \rightarrow e\gamma$ sensitivity consider an experiment that uses pixel detectors to track both the decay positron and the electron-positron pair from the converted photon. It has been shown that if BTeV pixel technology is used in an idealized geometry (Fig. 18), but with only 10% of the coverage of the old MEGA experiment, then a sensitivity that is comparable to the expected MEG sensitivity might be obtained at a beamline of the sort to be used by the BNL MECO experiment. Hence, pixel technology already offers an alternative to the traditional low mass tracking technology used in $\mu \rightarrow e\gamma$ experiments. The main limitation in using BTeV pixel technology would come from scattering in the fairly thick detectors. We can anticipate the development of much thinner pixel detectors. If, in the coming years, the pixel thickness can be reduced by a factor of 10, coverage increased to 50% of the MEGA coverage, and the readout rate improved by a factor of 20, then the resulting single event sensitivity would be improved by about two orders of magnitude. With even higher rate pixel detectors a

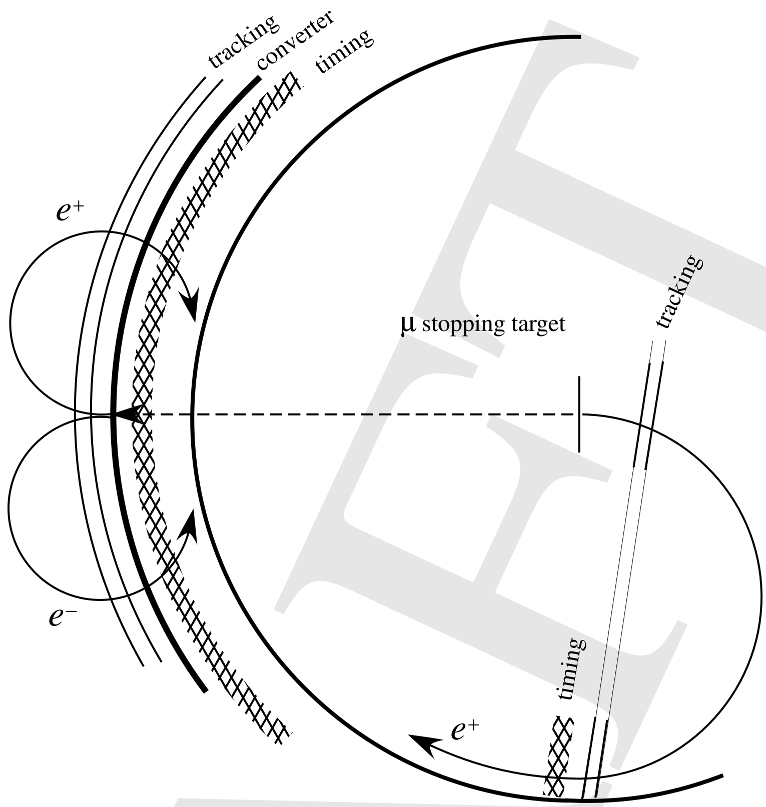


Figure 18: Fritzs egamma detector

further order of magnitude improvement might be possible.

Now consider $\mu \to e$ conversion. Within the context of SUSY extensions to the Standard Model, the $\mu \to e$ conversion rate is related to the $\mu \to e\gamma$ branching ratio:

$$\Gamma(\mu \to e\gamma) \sim 16\alpha^4 Z_{eff}^4 Z |F(q^2)|^2 BR(\mu \to e\gamma) \tag{5}$$

where $Z$ is the proton number for the target nucleus, $Z_{eff}$ is the effective charge, and $F(q^2)$ is the nuclear form factor. The $\mu \to e$ conversion rate normalized to the muon capture rate in Ti is then given by:

$$R(\mu^- \to e^- \, Ti) \sim 6 \times 10^{-3} BR(\mu \to e\gamma) \tag{6}$$

The prediction is model dependent, and hence searches for both $\mu \to e\gamma$ and $\mu \to e$ conversion are well motivated. The apparent suppression of the $\mu \to e$ conversion rate with respect to the $\mu \to e\gamma$ decay rate is in practice compensated by the higher sensitivity achievable for the conversion experiments. At BNL the MECO experiment is expected to achieve a sensitivity of O($10^{-17}$) in the coming decade. In the longer term the PRIME experiment has been proposed at JPARC to improve the sensitivity to O($10^{-19}$). Proton economics may well determine the fate of PRIME. If PRIME is not able to proceed at JPARC it might be accommodated at a Fermilab Proton Driver. If PRIME does proceed in Japan, a further generation experiment might be justified, but its design would presumably need to benefit from lessons learned with MECO and PRIME.

### 3.1.5 Other Muon Experiments

High precision future muon EDM, (g-2), and rare decay experiments, together with the possible development of a Neutrino Factory, provide the main particle physics motivation for desiring a new low energy high intensity muon source. There are however other measurements that might further enrich the scientific program at a new muon source, and provide an opportunity for smaller scale experiments. Muonium studies and precision muon lifetime measurements are examples of these types of experiment. Muonium experiments provide precision tests of QCD, precision measurements of the fine structure constant, $m_\mu/m_e$, the structure of the proton, and of course a search for lepton flavor violation. Many of these measurements are statistics limited. Higher precision muon lifetime measurements would provide a more precise value of the Fermi constant $G_F$. The theoretical uncertainty in the extraction of $G_F$ is $< 0.3$ ppm. At PSI the MuLAN experiment as attempting to measure $G_F$ with a precision of 1 ppm. A second PSI experiment, MuCAP, is measuring the muon capture rate to extract the pseudoscalar form factor $g_p$ with a precision of 7%. Further progress on measuring $G_F$ and $g_p$ will require high intensity muon beams with small spot sizes and tiny energy spreads. Hence, a muon source at a new Fermilab Proton Driver might provide a home for a further generation of these experiments.

## 3.2 Kaons

The search for quark-flavor physics beyond the Standard Model is a fundamental question for high-energy physics. It is now widely acknowledged that the critical decays in this search include the ultra-rare FCNC modes $K^+ \to \pi^+\nu\nu$ and $K_L \to \pi^0\nu\nu$. The SM expectations for the associated branching ratios are at the $3-7\times10^{-11}$ level. These decays probe quark flavor physics in the sector of $s \to d$ transitions. This provides us with information on new physics independently from, and in addition to, the results from B physics. Such information is essential since almost nothing is known about the flavor structure of new physics.

The $K \to \pi\nu\nu$ modes are ideally suited for this purpose since they are predicted in the SM with high theoretical accuracy. The intrinsic theoretical uncertainty on BR($K_L \to \pi^0\nu\nu$) is <1%. It is expected to reach 6% for BR($K^+ \to \pi^+\nu\nu$), in which the intrinsic theoretical uncertainty is dominated by the charm quark mass uncertainty.

The information from rare decays is also complementary to the direct production of new particles at high energies. Many crucial features of the quark-flavor sector, such as the nature of the couplings, can only be probed indirectly using rare decays. Examples from the past include the FCNC suppression via the GIM mechanism and CP violation, both discovered with K-decays. The variety of conceivable new physics scenarios involving $K \to \pi\nu\nu$ is very large. Specifically within many supersymmetric models, enhancements of 3x to an order of magnitude larger than SM expectation, are possible. In Minimal Flavor Violation models, an agreement of BR($K_L \to \pi^0\nu\nu$) with the SM prediction at the 1% level would constrain the new physics scale to exceed 12 TeV.

The world sample of $K^+ \to \pi^+\nu\nu$ consists of 3 candidate events observed by the combined BNL-E787 and BNL-E949 experiments. The experimental central value for the branching ratio is $1.5^{1.3}_{-0.9} \times 10^{-10}$, consistent with the SM expectation. There are currently no observed candidates for $K_L \to \pi^0\nu\nu$. A new generation of experiments has been proposed to observe 50-100 of each of these decay modes within the next 10 years. In the $K_L$ sector, the initiatives are KOPIO at BNL, and KEK391a and the follow-up experiment at JPARC (LOI-05). In the $K^+$ sector, the initiatives are JPARC-LOI-04, NA48/3 at CERN, and P940 at Fermilab. These will be exceedingly difficult experiments. Since they are searching for 3-body decays, and the neutrinos are not detected, there will be no mass peak, and high instantaneous rates from backgrounds that can exceed the signal by 10 orders of magnitude must be tolerated. A long spill length and debunched beam are necessary. In the proton driver era, assuming the presently proposed experiments meet their 50-100 event goal, a reasonable next goal would be to carry out measurements at the 1000 event level. However, the near term experiments are already pushing the limit of detector technology. Progress will therefore require improvements in detector technology. Nevertheless, there are reasons to hope that the required improvements will be made. Assuming this is the case we can estimate the required number of protons on target. We consider a KAMI-like beam line and detector for the $K_L \to \pi^0\nu\nu$ case, and use efficiency numbers from the KAMI proposal. For the $K^+ \to \pi^+\nu\nu$ case, we extrapolate similar quantities from the P940 proposal. The required numbers of protons on target are given in Table 7.

| Mode | Sample Size | Physics Measurement | POT |
|---|---|---|---|
| $K^+ \to \pi^+\nu\nu$ | 1000 | 3% of $\lvert V_{ts} * V_{td}\rvert$ | $1.5 \cdot 10^{20}$ |
| $K_L \to \pi^0\nu\nu$ | 1000 | 1.5% of $Im(V_{ts} * V_{td})$ | $1.6 \cdot 10^{21}$ |
| $K_L \to \pi^0 e^+ e^-$ | $2 \cdot 10^4$ | 10% of $Im(V_{ts} * V_{td})$ | $2.5 \cdot 10^{20}$ |
| $K_S - K_L \to \pi^0 e^+ e^-$ | $10^5$ | 10% of $Im(V_{ts} * V_{td})$ | $2.4 \cdot 10^{23}$ |
| $K_S - K_L \to \pi^0 e^+ e^-$ | $4 \cdot 10^5$ | 10% of $Im(V_{ts} * V_{td})$ | $2.5 \cdot 10^{23}$ |

Table 7: Desired data sample sizes for various kaon physics measurements in the Proton Driver era, and the associated number of protons on target (POT) needed.

Recently two additional decay modes have received attention: $K_L \to \pi^0 ee$ and $K_L \to \pi^0\mu\mu$. These decay modes are fully reconstructible, and therefore are significantly easier to identity than $K \to \pi\nu\nu$. There are no large backgrounds that could "feed-down" and fake the signal. The only serious backgrounds are $K_L \to ee\gamma\gamma$ and $\mu\mu\gamma\gamma$ which occur with a branching ratio of about $10^{-7}$ and can be reduced by kinematic cuts to obtain an effective residual background level of $\sim 10^{-10}$. Although this exceeds the expected signal by an order of magnitude, the background is flat over the signal region and with sufficient statistics the signal peaks would enable extraction of the branching ratios. The required numbers of protons on target are summarized in Table 7.

## 3.3 Pions

Pion experiments can provide precision tests of the Standard Model, searches for physics beyond the Standard Model, and measurements of light meson and baryon states that help us to develop a better understanding of the confinement and symmetry properties of QCD. In more detail:

(i) **Pion Decays** Pions are the lightest hadrons. Their decay modes are few and simple, and they therefore provide an exquisite laboratory for testing fundamental symmetries. It is generally agreed that the next important step in pion decay physics is to accurately measure the branching ratio of the decay $\pi^+ \rightarrow e^+\nu(\gamma)$ ($\pi_{e2}$) and normalize it to $\pi^+ \rightarrow \mu^+\nu(\gamma)$ ($\pi_{\mu 2}$). The double ratio $\mathrm{BR}(\pi_{e2})/\mathrm{BR}(\pi_{\mu 2})$ is theoretically clean, probes e-$\mu$ universality in weak charged decays, and is predicted in the Standard Model to have a value of $(1.2356 \pm 0.0001) \times 10^{-4}$. Beyond-the-SM scenarios typically preserve lepton universality in weak charged decays, and so it is believed to be a deeply fundamental symmetry. The current PDG2004 world average of the double ratio is $(1.230 \pm 0.004) \times 10^{-4}$. In comparison with lepton universality tests in $\tau$-decays or W-decays, the pion system's experimental precision is $3-10\times$ better and is unlikely to be surpassed. Increasing the precision of the pion measurements would be extremely valuable, as the theoretical prediction is currently 40 times more precise. In addition, the $\pi_{e2}$ measurement provides the normalization for measurements of the decay $\pi^+ \rightarrow e^+ n \pi^0$ decays ($\pi_\beta$). The uncertainty on the $\pi_{e2}$ measurements dominate the external systematic uncertainties on the $\pi_\beta$ measurement. This is of interest because the CKM matrix element $V_{ud}$ can be extracted cleanly from $\pi_\beta$ measurements. The current best $\pi_\beta$ measurement yields $V_{ud} = 0.9728(30)$. The PDG average is $V_{ud} = 0.9738(5)$, which is dominated by measurements from super-allowed nuclear decays. However, in the future, improved $\pi_\beta$ measurements would allow a theoretically cleaner extraction of $V_{ud}$, and improved precision provided the statistical and systematic uncertainties can be decreased. Finally, other rare pion decay modes that provide opportunities for searches for new physics are $\pi^0 \rightarrow 3\gamma$ for which the present best limit is $BR < 3.1 \times 10^{-8}$, $\pi^0 \rightarrow 4\gamma$ for which the present best limit is $BR < 2 \times 10^{-8}$, and $\pi^0 \rightarrow \nu\nu$ for which the present best limit is $BR < 8.3 \times 10^{-7}$. The PIBETA experiment at PSI is the current state-of-the-art charged pion decay experiment. PIBETA uses stopped pions. Neutral pion decays are studied using the charge-exchange reaction $\pi^- p \rightarrow \pi^0 n$. It is believed that the decay-at-rest technique is now at its systematic limit. At a Proton Driver, progress could be made by using decay-in-flight techniques. The main challenge would be to build an apparatus with reasonably large acceptance and, for the precision $\pi_{e2}$ measurement, understand the acceptance at the $10^{-3}$ level. The advantages that make the decay-in-flight technique worth pursuing are that (a) there would be no target-degrader material which greatly reduces the beam interaction background, (b) there would be no rate limitation due to the the 2 $\mu$ sec length of $\pi - \mu - e$ decay chain at rest and the higher energy decay products would allow a more efficient rejection of backgrounds arising from the $\pi - \mu - e$ decay chain, (c) the normalization of the pion flux could be measured absolutely by a device such as a beam Cerenkov detector, and (d) a decay-in-flight experiment could also measure $\pi^-$ decays. Hence, a Proton Driver could enable progress to be made beyond PIBETA.

(ii) **Meson and Baryon Spectroscopy**

Light meson and baryon spectroscopy probes the confinement and symmetry properties of QCD. Beyond the usual meson and baryon states, QCD predicts exotic bound configurations of quarks and gluons which include hybrids (e.g. $q\overline{q}g$ and $q^3g$), pure gluon states (e.g. $g^2$ and $g^3$), and multiquark states ($q^2\overline{q}^2$, $q^4\overline{q}$, ...). Only a small fraction of these exotic states have been observed. Observation of these states, together with measurements of their masses and widths, and determination of their quantum numbers, is needed to compare to the predictions of lattice gauge theory, flux tube models, etc. The spectrum of $q\overline{q}$ mesons is well known below 1.5 GeV. Above 1.5 GeV the low angular momentum states are poorly known. This is the region where many exotic states are expected. For example, lattice gauge theory calculations predict Glue Balls with masses from 2 - 5 GeV. Our knowledge of the baryon spectrum is also incomplete. The only reasonably well-known excited light baryon state is the D(1232), whose properties are known to $\sim 5\%$. The properties of a few other excited states, the lowest in each partial wave, are known to 30%. Properties of other 'known' states have much larger uncertainties. Therefore higher precision information is needed and missing states must be sought in N$\pi\pi$, $\Lambda$K, $\Sigma$K scattering experiments. The nuclear physics community have invested heavily in experimental and theoretical programs aimed at better understanding QCD. The flagship DOE nuclear physics program for spectroscopy currently uses the electromagnetic beam facilities at JLab. However, since the production mechanisms for the various exotic states are not well understood, it is important to use different types of beam. Indeed, the electromagnetic probes available at JLab cannot be analyzed without accounting for the hadronic intermediate states. Hence, pion beam experiments at an upgraded Proton Driver would permit progress in light meson and hadron spectroscopy that would complement the JLab program. The measurements would also provide tests of lattice QCD, and are therefore of interest to the particle physics community. The beam and detector requirements for meson and baryon spectroscopy studies are quite modest. The low energy secondary pion and kaon beams derived from the 8 GeV primary proton beam would be used. A high duty cycle would be desirable, and hence a bunch stretcher would be required. For baryon spectroscopy, a secondary beam momentum of 2.5 GeV/c with $\pi$/K tagging (via a beam Cerenkov detector) is needed. This corresponds to a resonance mass of 2.37 (2.43) GeV/$c^2$ in the $\pi$p (Kp) system. A secondary beam momentum spread of 5% is adequate, but the beam momentum should be measured to 1%. The beam channel should be designed to focus the beam 3-5 meters downstream from the target. This allows room for $4\pi$ detectors and shielding. Attention should be paid to keeping backgrounds low, particularly for neutral particle detectors. Polarized targets will be needed, and recoil polarization measurements will be desirable.

## 3.4 Other Potential Opportunities

In addition to physics opportunities that exploit neutrino, muon, pion, and kaon beams, a high intensity Proton Driver might also support a variety of other experiments or using other secondary beams or using electrons (accelerated in the linac between $H^-$ bunches, for example). Although all the possibilities have not been comprehensively explored, some specific examples using neutron beams and antiproton beams have been considered. These examples illustrate the long-term flexibility that a 2 MW Proton Driver would provide.

### 3.4.1 Neutrons

High power proton beams of a few GeV produce copious numbers of spallation neutrons in stopping targets. Dedicated neutron sources based on this production mechanism provide the highest peak neutron fluxes available for research purposes and provide time averaged fluxes that approach those available at the highest flux reactors. The primary scientific use for such sources lies in the application of neutrons in the thermal ($E \sim 25$ meV) and cold (1 meV $\leq E \leq$ 10 meV) regime for condensed matter research through the use of neutron scattering. In addition to this primary mission, spallation neutrons have research applications that transcend condensed matter research. Dedicated neutron scattering sources can address many of these auxiliary applications but there are others that, for a variety of reasons, are not appropriate at such facilities. A proton driver operating at 8 GeV and 2 MW would produce neutron beams with an intensity that is comparable to those from the most intense sources in the world. For many reasons including pulse structure, running time requirements, additional cost, as well as existing plans for comparable facilities, it is unlikely that the proton driver will be appropriate as a neutron source for neutron scattering. However, neutrons from production targets at the Proton Driver could be employed to support other types of experiment that will not be supported by next the generation of accelerator spallation sources. Potential opportunities include: 1) Production of Ultracold neutrons in a dedicated spallation target coupled to a superthermal converter, 2) Simulation of cosmic ray induced upsets of semiconductor devices, and 3) Search for neutron-antineutron oscillations. These experimental programs that are unlikely to be accommodated at the SNS or any other foreseen new facility. In more detail:

(i) **Ultracold Neutrons: Neutron Lifetime and Dipole Moment** Ultracold neutrons (UCN) are neutrons with sufficiently low kinetic energies that they can be confined in material or magnetic bottles. UCN have been used in a variety of important experiments including a search for the neutron electric dipole moment and the measurement of the neutron lifetime. Experiments of this nature are currently statistically limited by the intensity of existing UCN sources at high flux reactors. Recently a novel suggestion for the production of UCN using a spallation target has been undergoing tests at the Los Alamos Neutron Science Center (LANSCE) and elsewhere. The essence of the new method concerns the use of a small target that is very closely coupled to a solid deuterium UCN converter. The inelastic scattering of low energy neutrons from a solid deuterium target at low temperature is dominated by phonon scattering. It has been shown that by exposing a solid deuterium target at low temperature ( 5K) to a cold or thermal neutron flux, it is possible to create an ensemble of UCN which is not in thermal equilibrium with the incident neutrons. In this way it is possible to significantly increase the density of UCN from that obtained in the traditional cryogenic moderators currently in use. Such a system has relatively modest beam requirements. Due to heating effects in the solid $D_2$, it is unlikely that such a source can be run at high duty cycle. At most, such a source at the Proton Driver would require 1 linac pulse every few tens of seconds. To accommodate the possibility for such a source at the Proton Driver, one would desire the provision of a pulsed beam switch that would allow the extraction of an occasional pulse and a suitable experimental area to accommodate the source and experimental equipment. The implementation of such a system could provide the US with a significant opportunity to establish a national UCN facility for a variety of scientific programs.

(ii) **Neutron-Antineutron Oscillations** Experimental searches for nucleon decay have so far produced only lower limits on the nucleon lifetime. These limits have excluded the simplest GUT models based on (B-L)-conserving SU(5) GUT and SUSY-GUT schemes. To make further progress, it is of considerable interest to extend the search for baryon number non-conservation beyond the simple proton decay experiments. An important candidate for such an extended search is the B = 2 neutron-antineutron transition. The oscillation of a free neutron into an antineutron can be studied in very controlled experimental conditions. The current limit on a possible transition time between the free neutron and antineutron is $\sim$ 108 s. This sensitivity is essentially statistics limited. Largely because there are no suitable sources available for a new experiment, there are, at present, no concrete plans to improve this result. The Proton Driver may provide the only opportunity for an improved measurement of a possible neutron-antineutron transition using free neutrons. A 2 MW Proton Driver could be designed to be a very efficient source of cold neutrons with average flux equivalent to that of the $\sim$ 20 MW research reactor. Such a source would consist of a stopping target that is neutronically coupled to a cryogenic cold moderator. This system should be of sufficient size to allow the extraction of a relatively large cross-section cold neutron beam. If such a source were optimized for an oscillation experiment, it is estimated that the current limit could be improved by 2-3 orders of magnitude.

(iii) **Cosmic-Ray Induced Semiconductor Upsets** As feature size in semiconductors gets smaller and the number of gates per chip becomes larger, the susceptibility of integrated circuits to radiation induced single errors increase.

While it is well known that electronics in space may suffer disruptions from charged particles, it is less well known that cosmic ray induced upsets pose a non negligible issue for terrestrial electronics. At the Earth's surface and up to aircraft altitudes it is cosmic ray induced neutrons rather than charged particles that are the principle source of upsets. Such neutron induced single-bit upsets and single-bit latch-ups are rare but in fact pose a problem to systems that require very high reliability (i.e. aircraft avionics) or in systems which require sustained operation of a very large number of gates (i.e. super computers). Indeed, this problem has received sufficient attention that the Joint Electron Device Engineering Council (JEDEC) has developed standards for the measurement of such upset rates. Because the comic ray induced production process is very similar to the spallation process, it is not surprising that the primary spectrum of spallation neutrons is very similar to that of cosmic ray induced neutrons. Indeed, accelerator based spallation neutron targets are the only sources that provide a spectrum of neutrons intense enough for the accelerated testing of semiconductors. However, it is important to note that spallation sources that are optimized for neutron scattering for materials science are designed for the extraction of only very low energy neutrons (typically a few meV?s). As a result, the beamlines at such facilities do not provide neutrons in the range of interest for single event upset tests ( 10-100 MeV). At present there is only one facility in world, the Weapons Neutron Research (WNR) facility at Los Alamos, that provides suitable beams. To accommodate the possibility of such a facility would require the provision for a beamline that would view a high current stopping target. A shutter and provision for an appropriately shielded irradiation facility would also be required.

### 3.4.2 Antiprotons

The antiproton source at Fermilab was designed and built to collect antiprotons for use at high energy in the Tevatron Collider. Although this is its primary use, in the past it has also been used to put stringent limits on the antiproton lifetime and, with a gas-jet target, to study charmonium states. It also provided the first unambiguous observation of atomic antihydrogen.

For the next several years the Tevatron Collider will operate at the highest possible luminosity and will therefore use all of the antiprotons that the antiproton source can provide. In the Proton Driver era, beyond collider operations, the Fermilab antiproton source could be exploited for other physics. At that time, there will exist only one, or possibly two, other antiproton sources in the world - one at GSI, and possibly one at CERN. The Fermilab source will likely be by far the most intense source of antiprotons in the world, especially because the Proton Driver is expected to improve the source intensity by up to a factor of two over the intensity expected at the end of Collider Run II. Thus Fermilab could host antiproton experiments with beam energies and/or intensities that are higher than those available elsewhere. Some examples of physics topics that might be of interest at a Proton Driver era antiproton source are:

(i) **Quarkonium Formation** The study of the charmonium and bottomonium systems has been crucial in unraveling the short-distance properties of the strong interaction. While most of the data have come from electron-positron interactions, a significant number of important measurements have been made in studies of antiproton-proton formation of charmonium. Note that only $1^{--}$ states are directly formed by $e^+e^-$ annihilation, although $0^{++}$ and $2^{++}$ states are formed in two-photon interactions. Other states must be studied in $1^{--}$ decays, yielding poor precision on masses and widths. Some of the most important states are difficult to reach in $1^{--}$ decays (e.g. $1^{+-}$ and $0^{+-}$ states). In particular the $h_c$ and $\eta_c'$ states are reported but unconfirmed, and the $h_b$, $\eta_b$ and $\eta_b'$ states are undiscovered. In $\bar{p}p$ formation all non-exotic mesons can be formed. Because of synchrotron radiation losses, the energy spread in $e^+e^-$ colliders is large (several MeV). In an antiproton storage ring, the energy spread can be 10-100 keV allowing precise measurements of heavy- quarkonium masses and widths. Of potential interest to a Proton Driver era antiproton source program are: (a) In charmonium the $h_c$ must be confirmed, the significant mass discrepancy between the BELLE and BABAR sightings of the $\eta_c'$ resolved, the $h_c$ and $\eta_c'$ widths measured, and the other narrow states identified and characterized, namely the $\eta_{c2}(1^1D_2)$, $\psi_2(1^3D_2)[X(3872)?]$, $1^3D_3$, $2^3P_2$, and $1^1F_4$. The interesting charmonium measurements could be made using a gas jet target in the Antiproton Accumulator, with a spectrometer similar to the E835 spectrometer. (b) In bottomonium the 1S, 2S, 1P and 2P singlet states are unobserved and the 1P and 2P $\chi_b$ masses have been measured at the 1 MeV level, but the widths are not yet measured. D states of bottomonium have not been observed. In order to study bottomonium, it will be necessary to build a new facility. The branching ratio of bottomonium states to $\bar{p}p$ have not yet been measured, so the formation cross section is unknown, but is expected to be small. The states are narrow, thus high luminosity and very small beam energy spread are required. We expect, for example $\chi_b$ formation cross sections to be no larger than $\sim$1 nb and $\chi_b$ widths to be $\sim$ 100 keV [84]. Therefore, the instantaneous luminosity should be at least $10^{32}$ cm$^{-2}$s$^{-1}$ and the $s^{1/2}$ resolution $\sigma_E <$ 100 keV. In the previous CERN and FNAL experiments, a hydrogen-gas-jet target intersected a high-current cooled stored $\bar{p}$ beam; E835 reached $L \sim 5 \times 10^{31}$ and $\sigma_E \sim 100$ keV at charmonium energies. A similar bottomonium experiment would require a $\bar{p}$ storage ring with variable energy between 46 and 56 GeV with $\Delta p/p \sim 10^{-5}$. An alternative design would be a symmetrical $\bar{p}p$ collider operating at 4.5-5.5 GeV per beam, again with $\Delta p/p \sim 10^{-5}$. It appears plausible to achieve the required luminosity. Such a machine could be designed to operate at charmonium energies at a smaller luminosity, which would be acceptable for that physics. We note that this machine would fit nicely into the Booster tunnel.

(ii) **CP Violation in Hyperon Decays** The Standard Model (SM) predicts a slight $CP$ asymmetry in the decays of hyperons [85–91]. The most accessible signal, the fractional difference in the magnitudes of the $\alpha$ decay parameters [92] for a hyperon and its antiparticle [88,89,93,94], is predicted in the SM to be of order $10^{-5}$ for $\Lambda$ decay [85–91]. In various extensions of the SM these can be much larger; for example, the supersymmetric calculation of He *et al.* [95] generates asymmetries as large as $1.9 \times 10^{-3}$. Sensitive measurements of hyperon and antihyperon decay can thus provide a new window into the underlying mechanism of *CP* violation. Table 8 summarizes the experimental situation. The first three experiments cited studied $\Lambda$ and $\overline{\Lambda}$ decay only [96–98]. Fermilab experiments E756 [99] and HyperCP (E871) [100–102] and CLEO [103] employed the cascade decay of charged $\Xi$ and $\overline{\Xi}$ hyperons to produce polarized $\Lambda$'s and $\overline{\Lambda}$'s, in whose subsequent decay the (anti)proton angular distribution measures the product of $\alpha_\Xi$ and $\alpha_\Lambda$.

| Expt. | Facility | Mode | $A_\Lambda$ [*] or $A_{\Xi\Lambda}$ [†] | Ref. |
|---|---|---|---|---|
| R608 | ISR | $pp \to \Lambda X, pp \to \overline{\Lambda} X$ | $-0.02 \pm 0.14^*$ | [96] |
| DM2 | Orsay | $e^+e^- \to J/\psi \to \Lambda\overline{\Lambda}$ | $0.01 \pm 0.10^*$ | [97] |
| PS185 | LEAR | $\overline{p}p \to \overline{\Lambda}\Lambda$ | $0.006 \pm 0.015^*$ | [98] |
| E756 | FNAL | $pN \to \Xi^- X, \Xi^- \to \Lambda\pi^-$<br>$pN \to \overline{\Xi}^+ X, \overline{\Xi}^+ \to \overline{\Lambda}\pi^+$ | $0.012 \pm 0.014^\dagger$ | [99] |
| CLEO | CESR | $e^+e^- \to \Xi^- X, \Xi^- \to \Lambda\pi^-$<br>$e^+e^- \to \overline{\Xi}^+ X, \overline{\Xi}^+ \to \overline{\Lambda}\pi^+$ | $-0.057 \pm 0.064 \pm 0.039^\dagger$ | [103] |
| HyperCP$^\ddagger$ | FNAL | $pN \to \Xi^- X, \Xi^- \to \Lambda\pi^-$<br>$pN \to \overline{\Xi}^+ X, \overline{\Xi}^+ \to \overline{\Lambda}\pi^+$ | $(0.0 \pm 5.1 \pm 4.4) \times 10^{-4\dagger}$ | [102] |

$^\ddagger$Based on ≈5% of the total HyperCP dataset.

Table 8: Summary of experimental limits on *CP* violation in hyperon decay.

It is difficult to see how the HyperCP approach can be extrapolated to $10^{-5}$ sensitivity. However, the approach of PS185 may yet have significant "headroom" [104]. In 1992, Rapidis, et al. (P859) proposed to look for CP violation in the $\alpha$ parameter of $\Lambda$ decay using the reaction $\overline{p}p \to \overline{\Lambda}\Lambda$ with a hydrogen gas jet target and a $\overline{p}$ beam energy of 1.641 GeV/c (above threshold for $\overline{\Lambda}\Lambda$ but below threshold for $\overline{\Lambda}\Sigma$). The experiment proposed building a small storage ring which could accept 3 GeV/c antiprotons from the Accumulator and decelerate them to the desired energy. The proponents of P859 estimated that they could reach a sensitivity of $10^{-4}$ in the fractional difference between the $\Lambda$ and $\overline{\Lambda}$ $\alpha$ parameters in three months of running, consuming 6 mA of $\overline{p}$ current from the Accumulator per hour. Since 1992, the HyperCP experiment, which was also designed to study CP violation in hyperon decays (either $\Lambda$ or $\Xi$) has been run. HyperCP has not yet published its final result, but it is likely that this experiment will achieve a sensitivity close to the $10^{-4}$ level that was the goal of P859. If systematics can be handled, it might be possible to reach the $10^{-5}$ level using the technique proposed by P859. This would require 100 times more events, but this sample could be collected in a few years, even assuming that the experiment used only one half of the total number of antiprotons provided by the antiproton source (assuming a stacking capacity of 80 mA/hour).

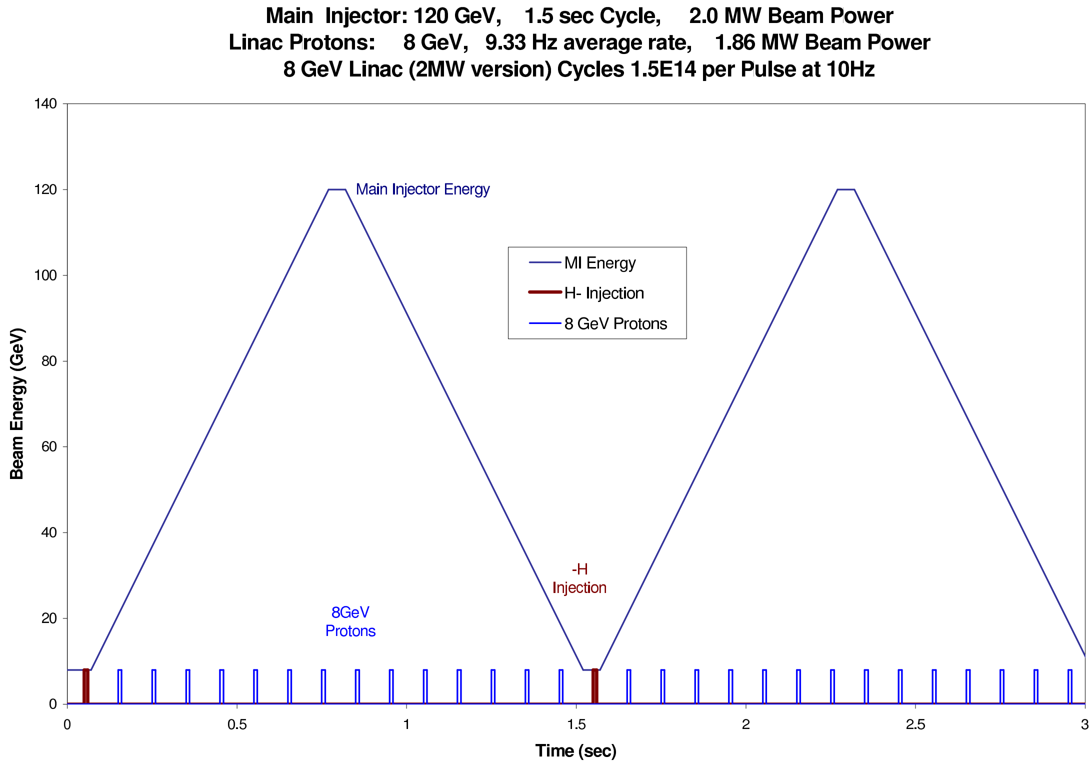


Figure 19: Proton Driver bunch structure and the Main Injector cycle.

# 4 Compatibilities and Proton Economics

The proton driver design that is currently favored consists of an 8 GeV $H^-$ Linac that initially would produce a 0.5 MW beam, and that can eventually be upgraded to produce a 2 MW beam. A small fraction of the 8 GeV beam would be used to fill the MI with the maximum beam that, with some modest improvements, it can accelerate. This would yield a 2 MW beam at MI energies. Hence the upgraded proton source would deliver two beams that can be simultaneously used for experiments: a 2 MW beam at MI energies, and eventually an almost 2 MW beam at 8 GeV. To illustrate this the cycle structure is shown in Fig. 19. The MI would receive one pulse from the Linac every 1.5 sec. The cycle time is dominated by the time to ramp up and ramp down the MI energy. The 14 Linac pulses that are available, while the MI is ramping and at flat top, would provide beam for an 8 GeV program.

The initial NUE long-baseline program would be expected to be the primary user of the 2 MW MI beam. The high-energy neutrino scattering program also needs this beam, and would be expected to coexist with NUE. The other candidate uses of the MI beam include supporting experiments at an antiproton source, and supporting kaon experiments. The antiproton source could operate in parallel with the MI neutrino program with a modest reduction in the available POT for the NuMI beam. The kaon program, in contrast to the neutrino program, would require a slowly extracted beam. However, with an additional storage ring, it is possible that a kaon program could be run during neutrino running with only a minor impact on the POT available for the neutrino program. This could be accomplished by fast extraction of a fraction of the MI bunches and transfer into a stretcher ring. The protons stored in the ring would then be slowly extracted for the kaon program. A ring in the Tevatron tunnel would be ideal for this purpose.

The candidates for using the 8 GeV beam are a low energy neutrino scattering experiment, a pion program, a muon program, and a neutron program. The neutrino scattering experiment requires short pulses with large gaps between pulses so that beam-unrelated backgrounds can be suppressed. The pion program requires a beam stretcher to produce long pulses and hence minimize the instantaneous intensity. Many experiments in the muon program require a CW beam with bunches that are short compared to the muon lifetime with gaps between bunches of several muon lifetimes. Hence all of these programs will require an additional storage ring to manipulate the bunch structure. It is possible that, in the post-collider era, this storage ring could be the Recycler. Noting that each of these 8 GeV sub-programs requires a different bunch structure it is natural to consider a scenario in which they run sequentially rather than in parallel. To illustrate this, we can imagine that initially an 8 GeV neutrino scattering experiment is the primary user of the 8 GeV beam, followed by (or possibly interleaved with) one or more pion experiments. In a second phase the facility is upgraded to include a low energy muon source, and one or more low energy muon experiments become the primary user(s). In a third phase, if required, the muon source could be developed to become the front-end of a neutrino factory. This could be a very long-term 20 - 30 year plan.

# 5 Summary

There is a compelling physics case for a Proton Driver at Fermilab. This upgrade to the existing accelerator complex is motivated by the exciting developments in neutrino physics. Independent of the value of the unknown neutrino mixing parameter $\theta_{13}$, a 2 megawatt Main Injector proton beam would facilitate, over the coming decades, one or more long-baseline neutrino experiments that would make critical contributions to the global neutrino oscillation program. The NuMI beam is the only neutrino beam in the World with an appropriate energy and a long enough baseline for matter effects to significantly change the effective oscillation parameters. With a 2 megawatt Proton Driver this unique feature of the Fermilab neutrino program can be exploited to:

- Probe smaller values of $\theta_{13}$ than can be probed with reactor-based experiments or with any existing or approved accelerator-based experiment.
- If $\theta_{13}$ is not very small, determine the neutrino mass hierarchy and greatly enhance the sensitivity of the global neutrino program to CP violation.
- If $\theta_{13}$ is very small, establish the most stringent limit on $\theta_{13}$ and prepare the way for a neutrino factory driven by the Proton Driver.

The MI neutrino oscillation physics program would be supplemented with a broad program of neutrino scattering measurements that are of interest to particle physicists, nuclear physicists, and nuclear astrophysicists. The neutrino scattering program would utilize both the Proton Driver upgraded NuMI beam, and neutrino and antineutrino beams generated using the protons available at 8 GeV. The overall neutrino program motivates the highest practical primary beam intensities at both MI energies and at 8 GeV. In practice this means 2 megawatts at MI energies and 0.5-2 megawatts at 8 GeV.

Additional physics programs could also be supported by the Proton Driver. In particular, the Proton Driver could support (i) a program of low energy experiments that probe the TeV mass scale in a way that is complementary to the LHC experiments, and (ii) a program of low energy experiments that are of interest to the nuclear physics community and that is complementary to the JLab program. The possibilities using the 8 GeV beam include (i) the development of a very intense muon source with a bunch structure optimized for (g-2), muon EDM, and LFV muon decay experiments, (ii) a program of low energy pion experiments, and (iii) some specific experiments using spallation neutrons. The possibilities using the MI beam include a program of kaon experiments, and some specific experiments using the antiproton source.

For decades to come, a Fermilab Proton Driver would support an exciting world class neutrino program that would address some of the most fundamental open questions in physics, and could also support a broader program of low energy experiments.

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